Microscopie et Spectroscopie Tunnel à Balayage dans l'étude des systèmes à fortes corrélations électroniques

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Ecole MICO 2010

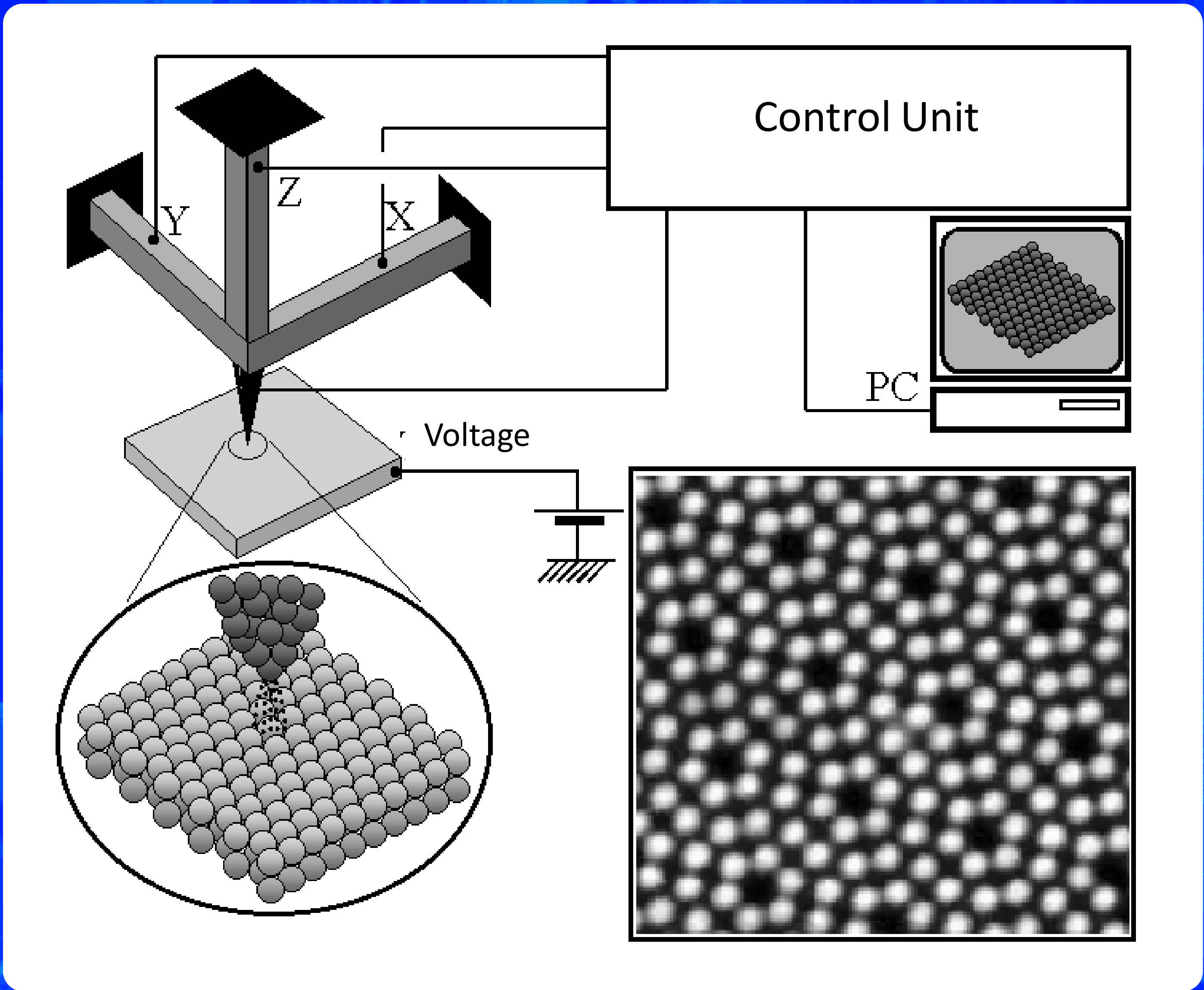
OUTLINE

Scanning Tunneling Microscopy (STM) and Spectroscopy (STS)

1. Physical background
2. How to make it, how it looks like
3. Spectroscopy of Superconductors
4. Other strongly correlated materials

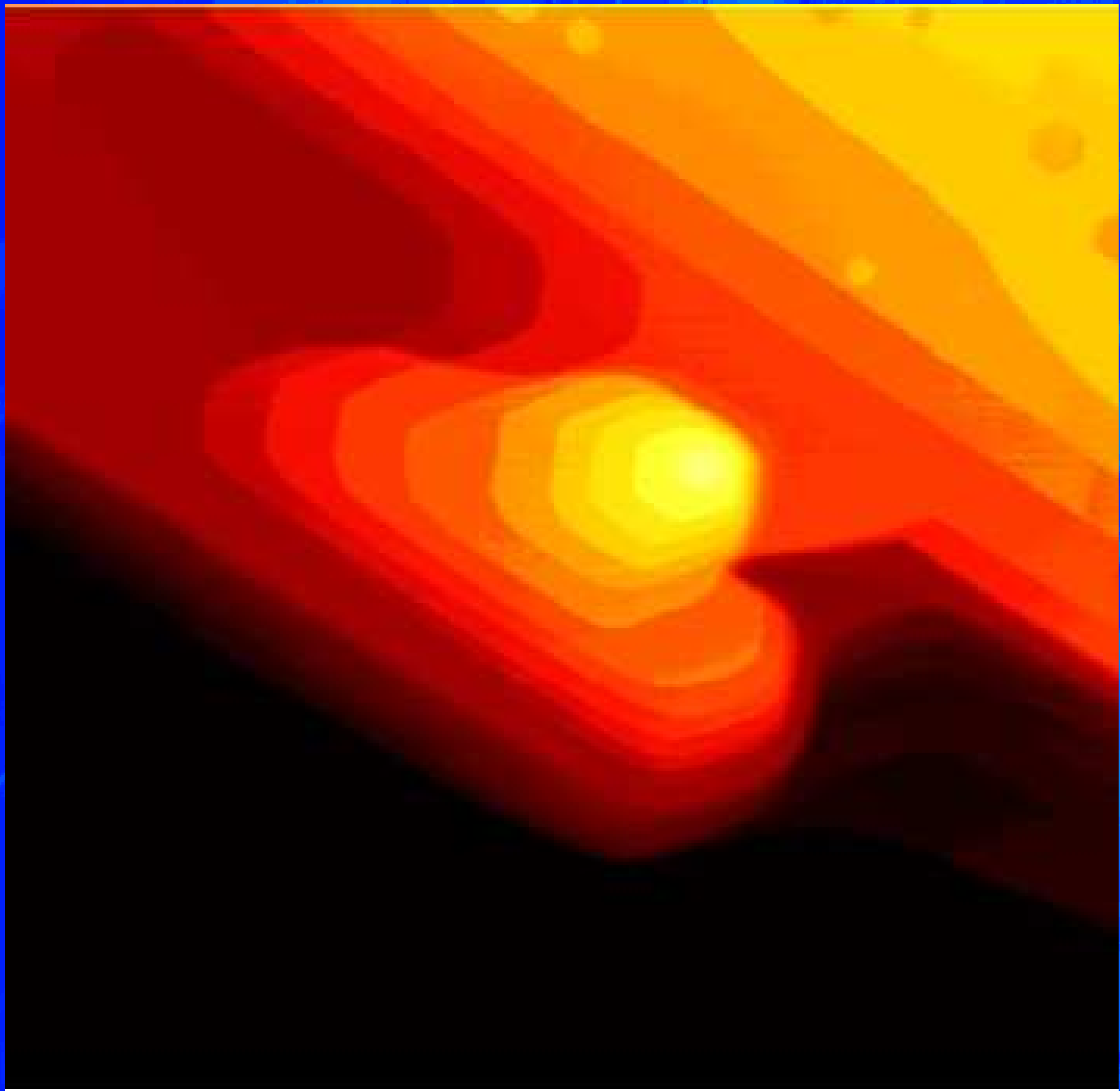
Invention du STM

Depuis 1982 : Scanning Tunneling Microscope
par G. Binnig et H. Rohrer , Prix Nobel 1986

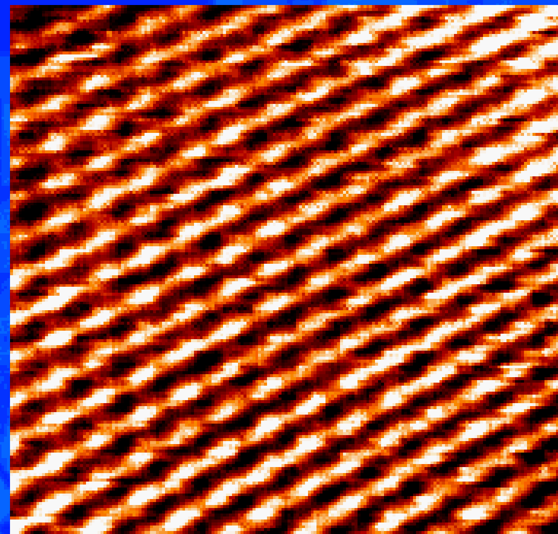


Surface Study by STM

Ag(111) at 300K



Ag(111) at 300K:
Atomic corrugation *2pm*

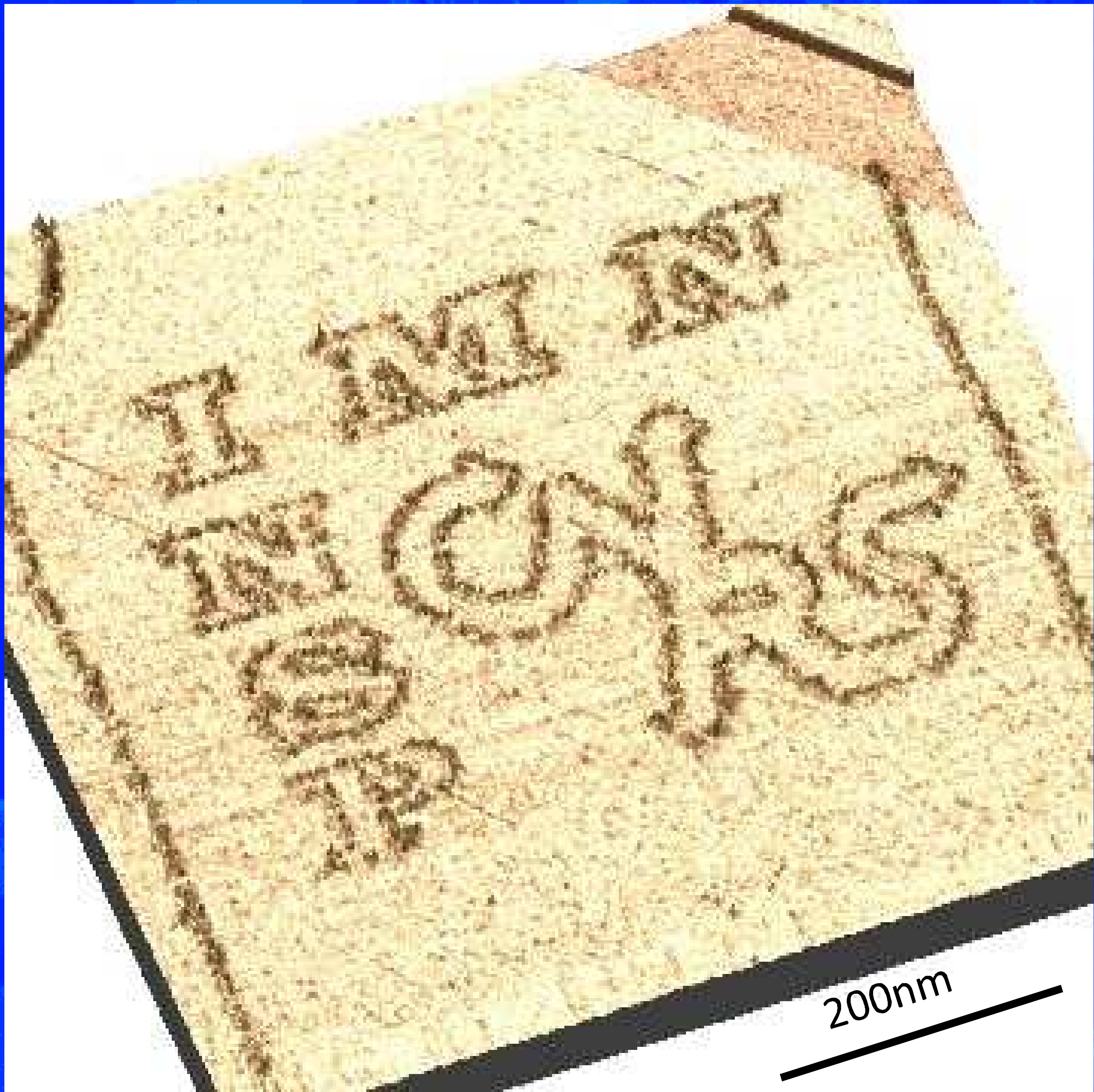


STM Controlled Growth

Pb-Morphology: 3 ML + Islands

Selection of Heights due to Z
- Quantum Confinement

Nano-Writing with STM

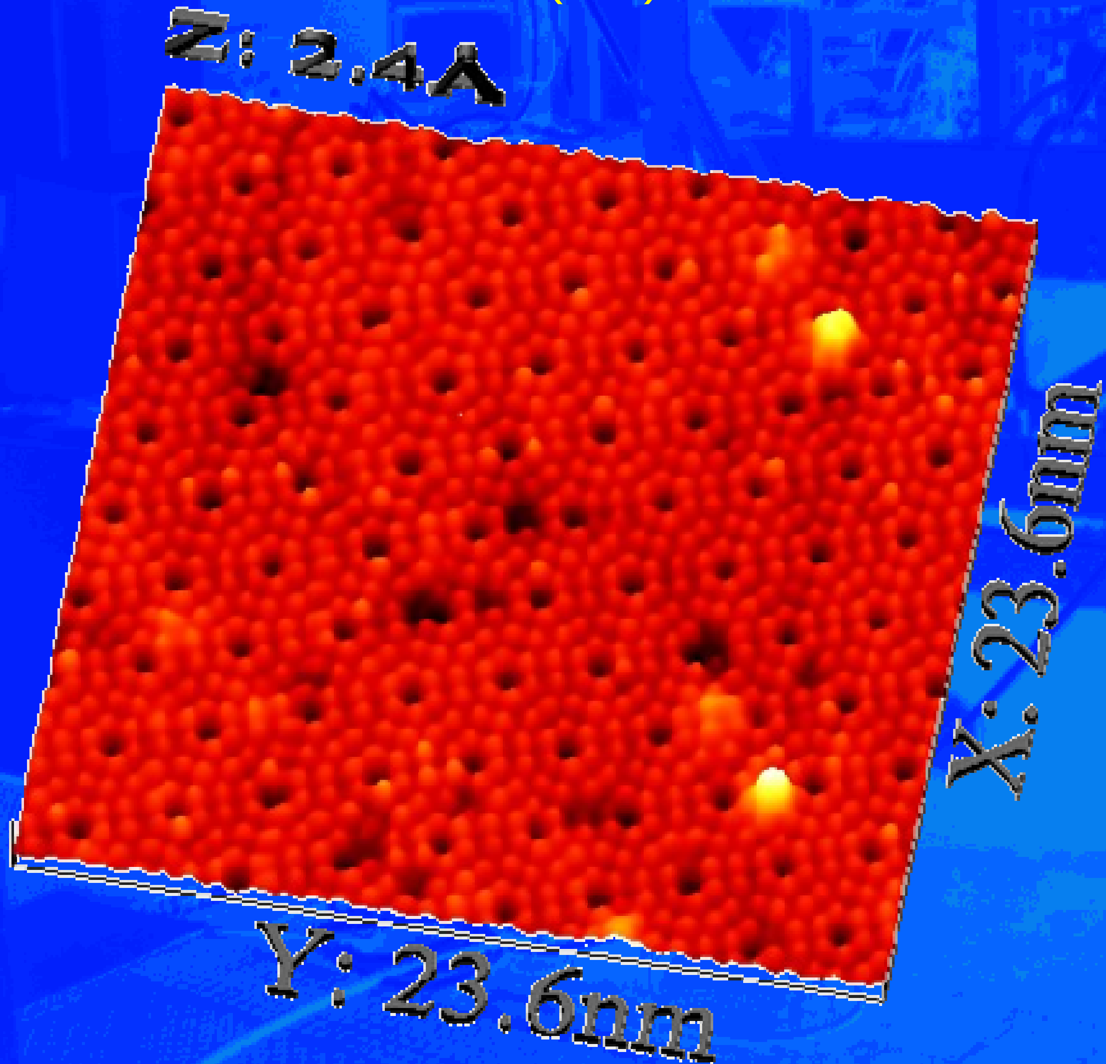


Collaboration:
L. Cario et al.
IMN, UMR6502,
Université de Nantes

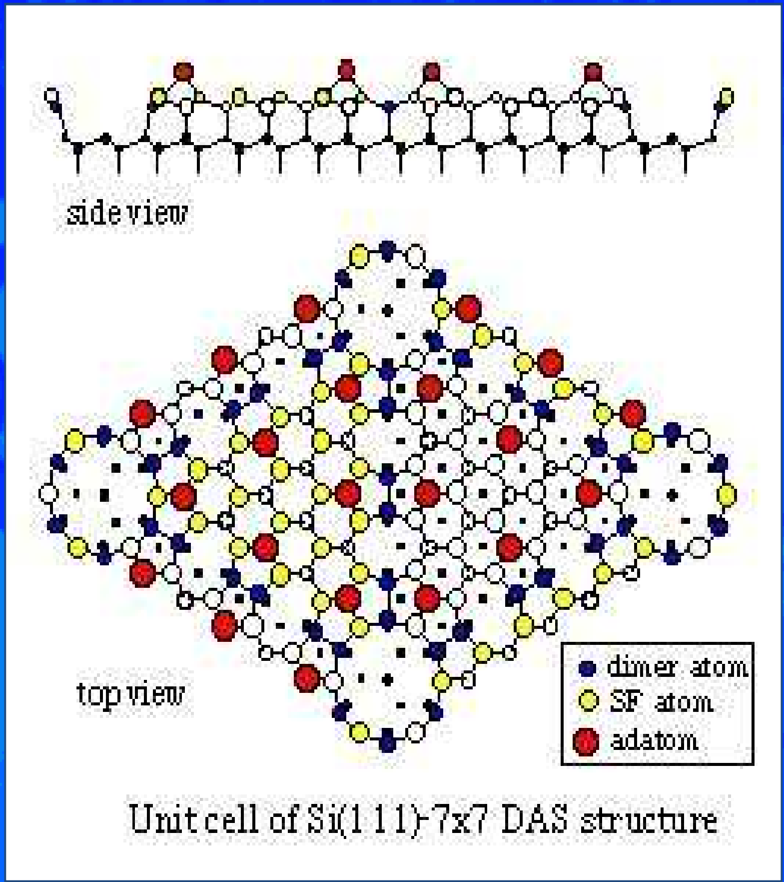
Atomic pattern resolved by STM

Silicon: an ideal substrat

Si(111)

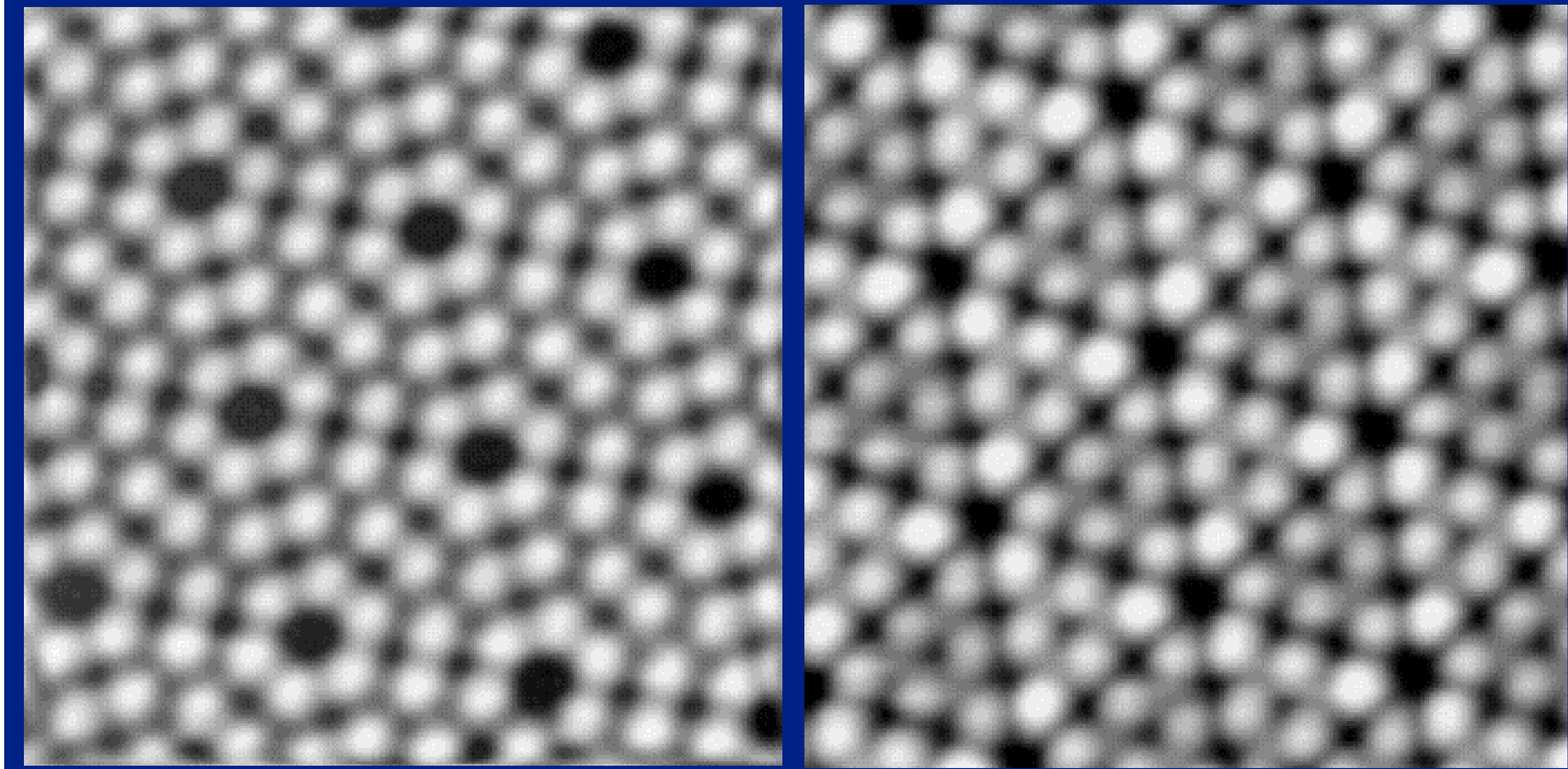


Surface Reconstruction 7x7



Au-delà de la topographie STM

- ***Si(111)-7x7 Surface***



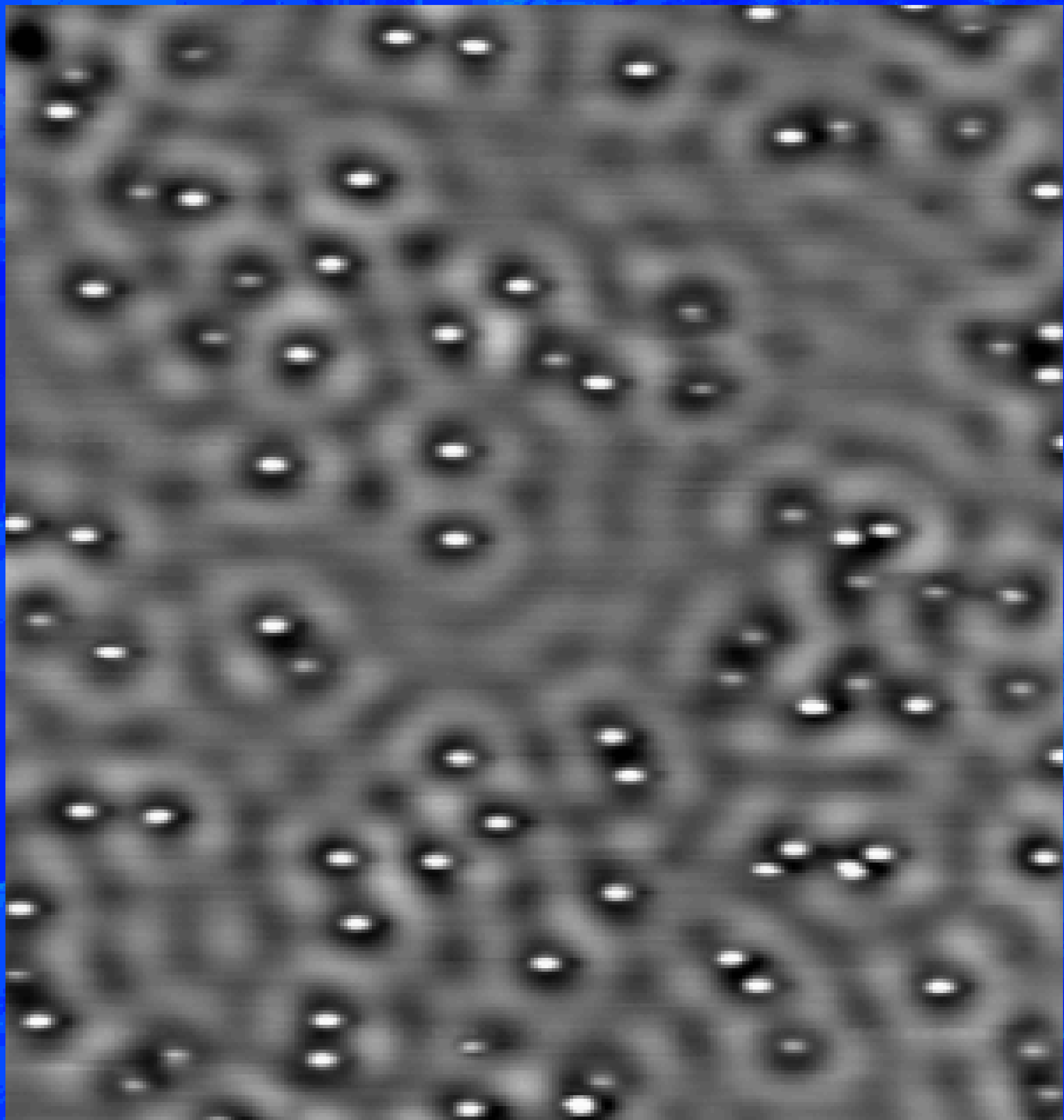
Empty-State Image

Imaging: Vs=2V, I=0.6nA

Filled-State Image

Imaging: Vs=-2V, I=0.6nA

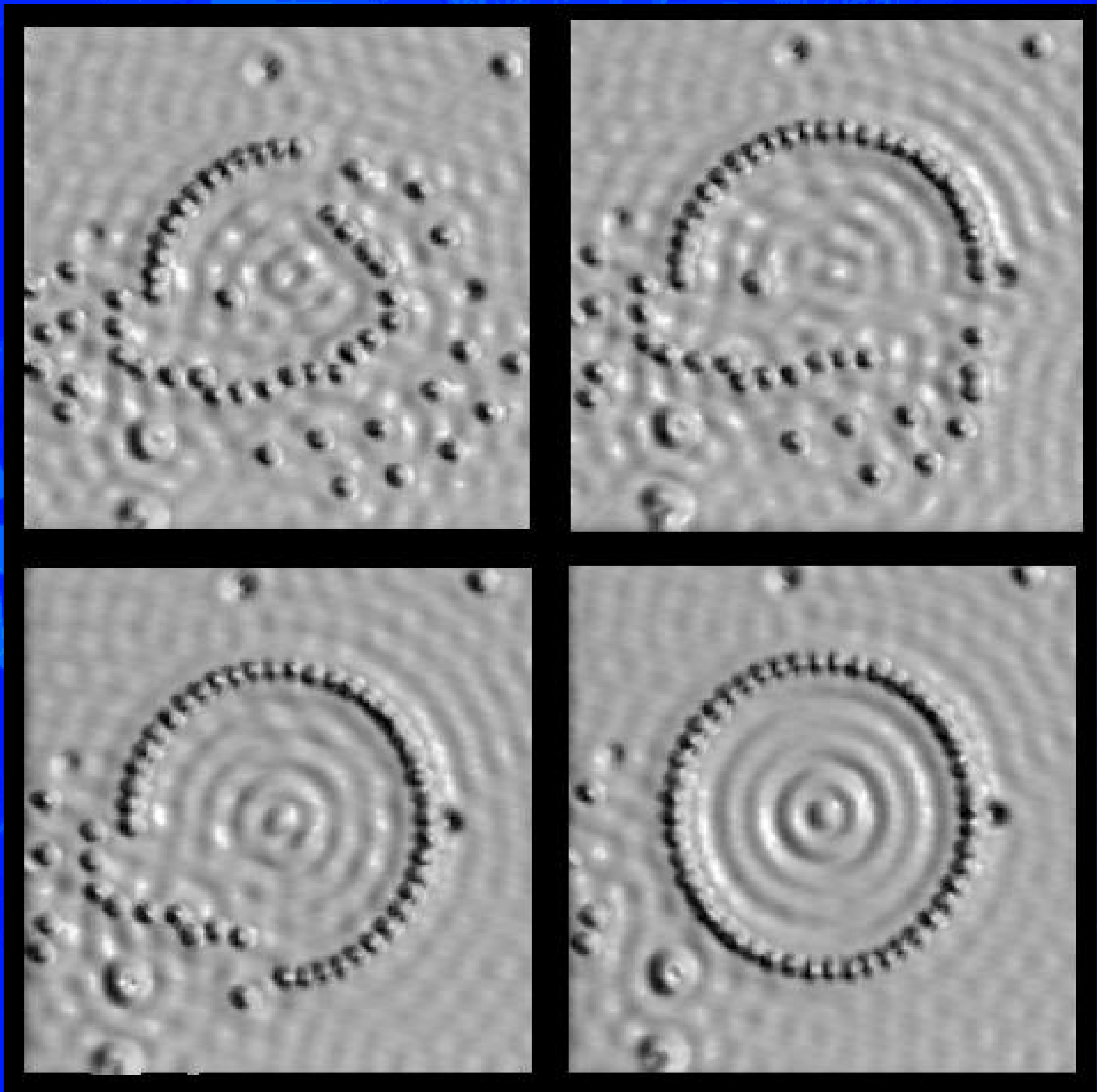
Atomes de Co sur la surface d'Ag



T. Cren et al.
EPFL Lausanne

T = 30 K (-243℃)
Ultra-vide

Quantum Resonator



● Fe atoms at Cu (111)

T = 4,2 K (-269℃)
UHV

D. Eigler et col.
IBM Research Division, Almaden Research Center, California,USA

site WEB: http://www.almaden.ibm.com

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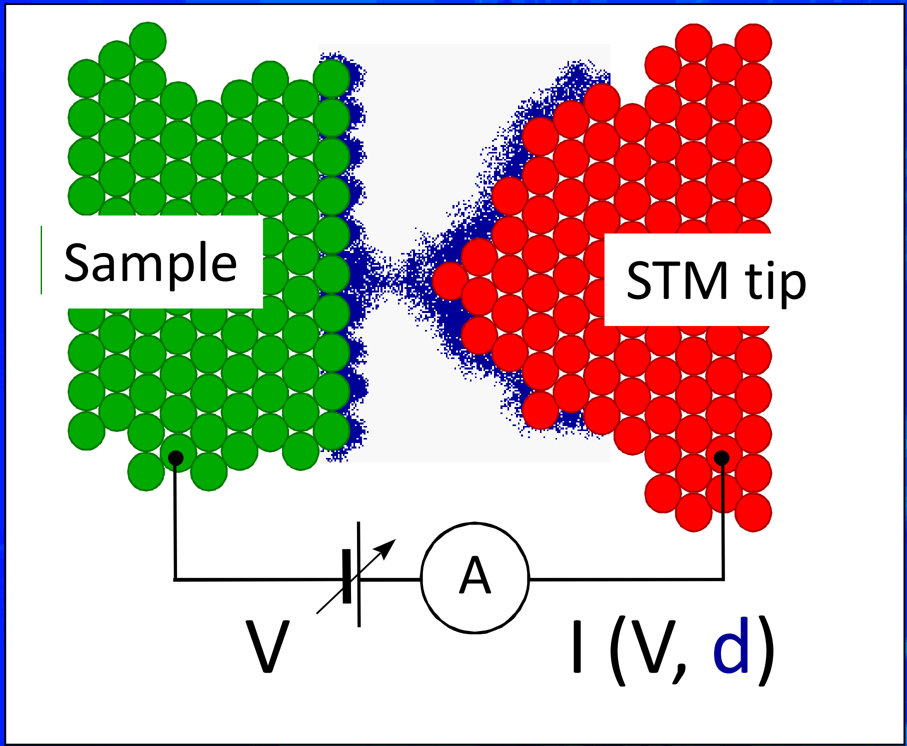
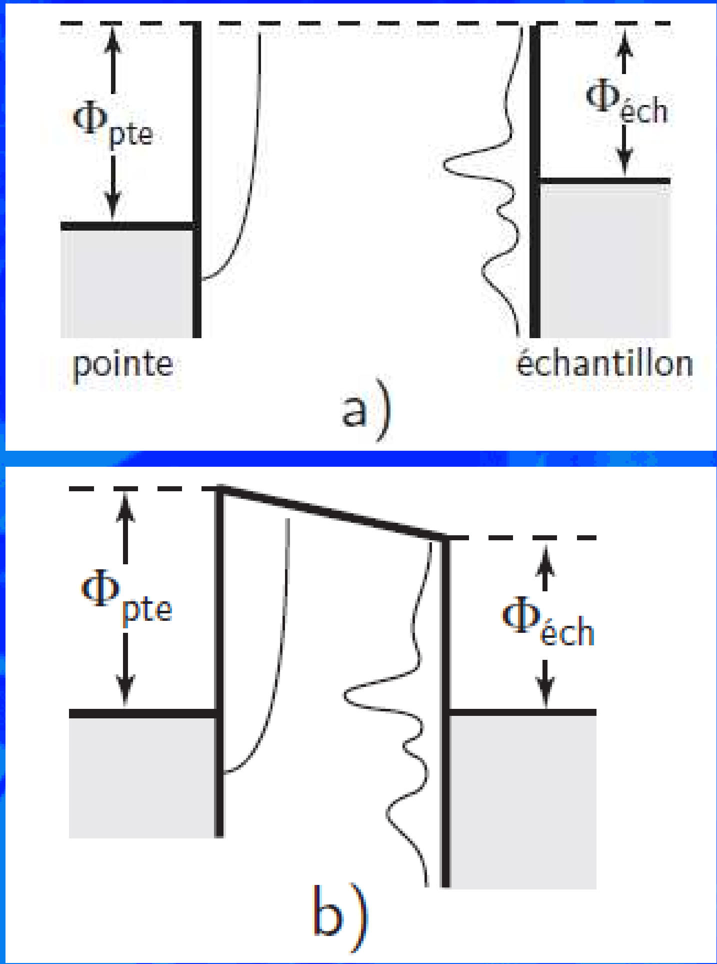
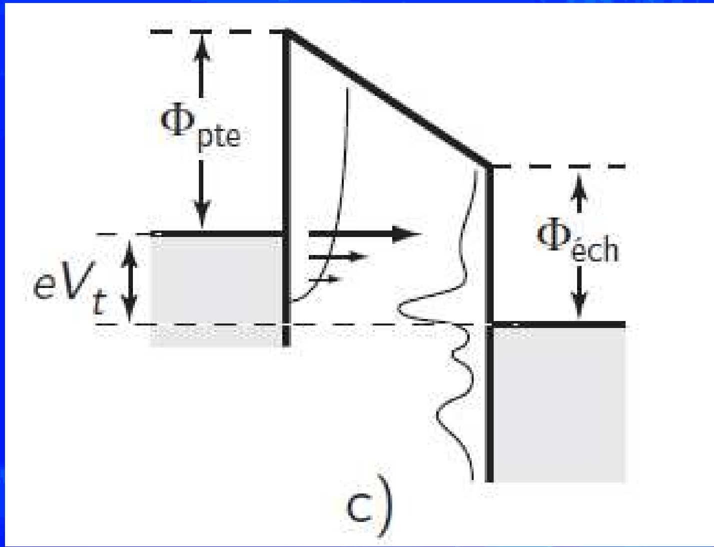
STM/STS: Local Tunneling Junction

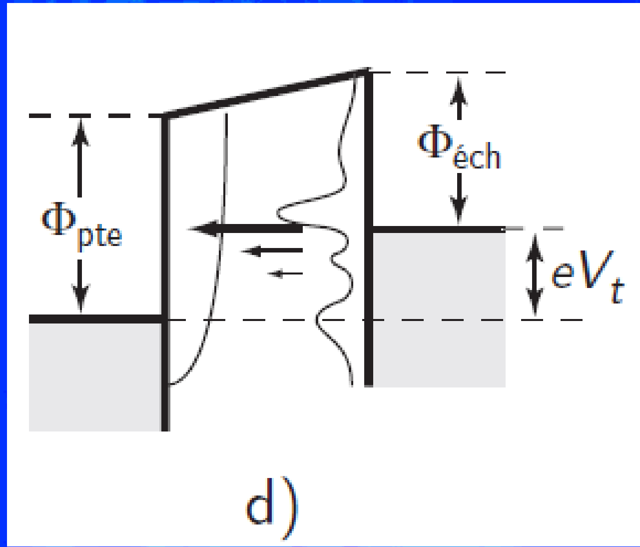




N.B. STM junction =
Sample + Tip + Cable + Battery (+ Ampermeter)

Tunneling Junction at T > 0K





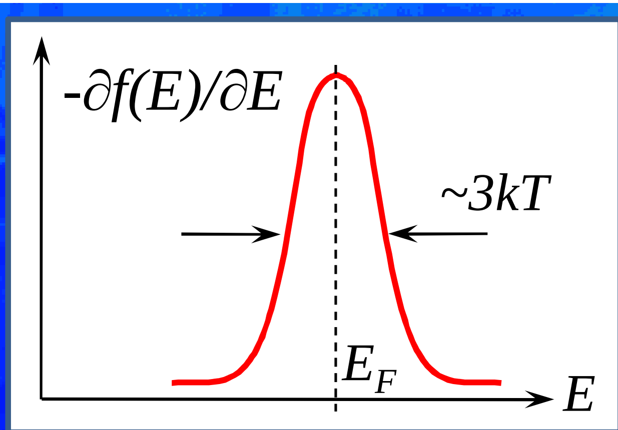
$$I = \frac{2\pi e}{\hbar}\int_{-\infty}^{\infty} T N_s(E-eV)N_p(E)[f(E-eV)-f(E)]dE$$

If $N_P(E), T(E) = const$

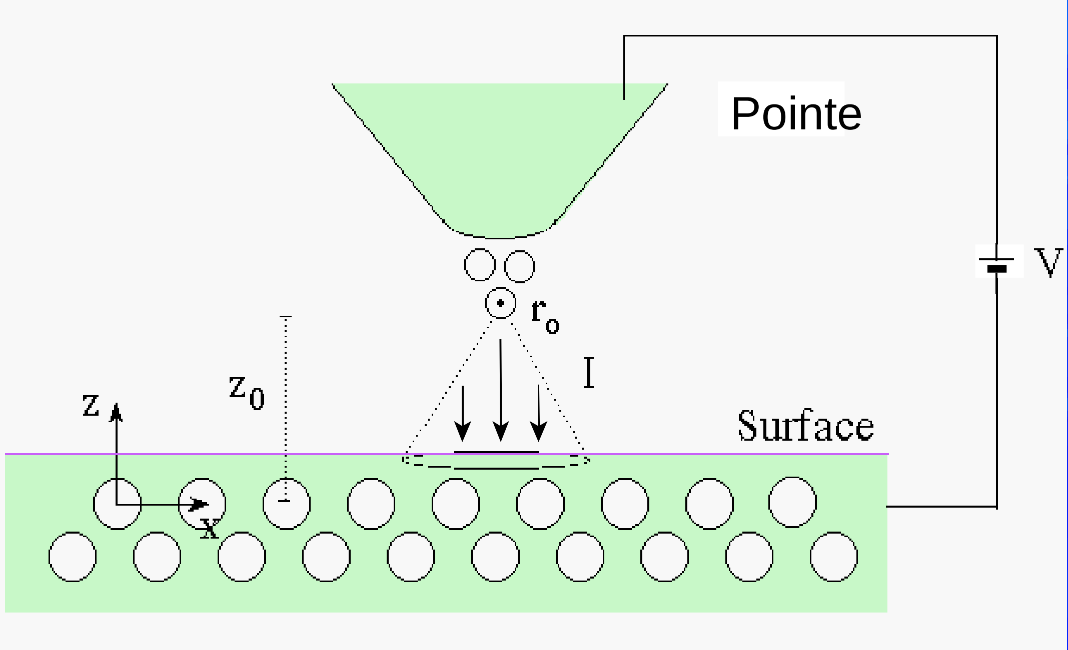
$$\frac{dI}{dV}(V) = -\frac{2\pi e^2 T}{\hbar} N_p \int_{-\infty}^{\infty} N_S(E+eV)\ \frac{\partial f}{\partial E}(E)dE$$

At zero Temperature $T = 0$:

$$\frac{dI}{dV}(V) = \frac{2\pi e^2 T}{\hbar} N_P\ N_S(eV) \quad !$$



Local Tunneling Junction at T > 0K



J. Tersoff et D. R. Hamann, Phys. Rev. Lett. 50, 1998 (1983).

A. Selloni, et al. Phys. Rev. B 31, 2602 (1985).

N. Lang, Phys. Rev. B 34, 5947 (1986).

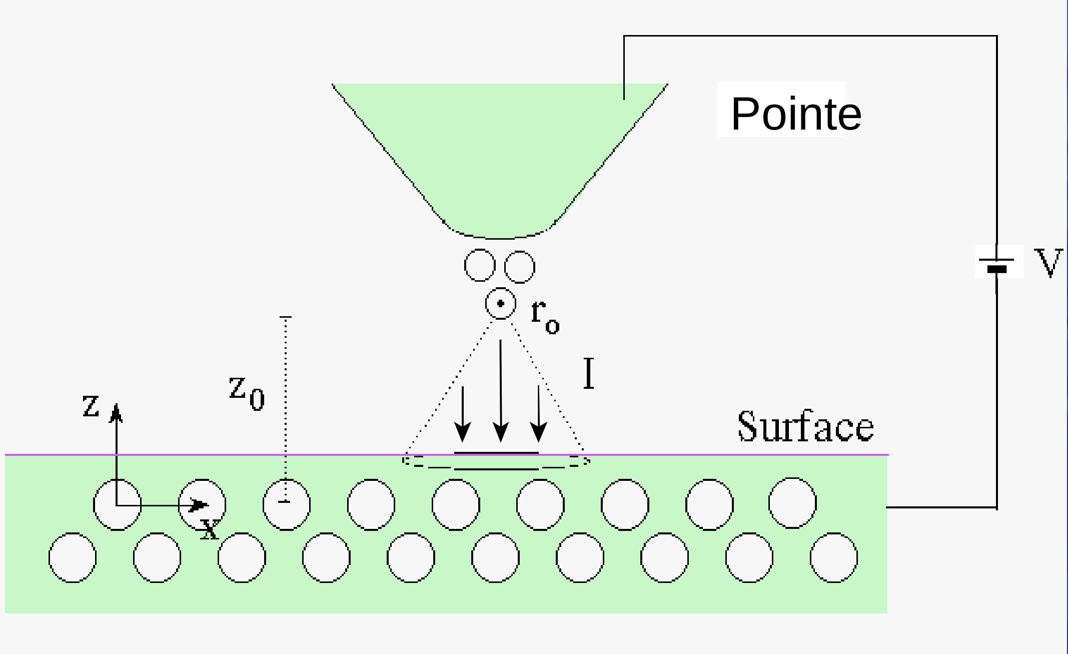
$$I(V,T,x,y,s) \propto \int_{-\infty}^{\infty} dE\, \rho_{\text{éch}}(E,x,y,s)\, \rho_{\text{pte}}(E-eV) \times T(E,V,s)\left[f(E-eV,T)-f(E,T)\right]$$

$$\rho_{\text{éch}}(E,x,y,s) = \sum_k |\psi_k(\mathbf{r})|^2\, \delta(E-E_k)$$

LDOS
Local Density of States

$$T(E,V,s) = \exp\left(-2s\sqrt{\frac{m_e}{\hbar^2}}\sqrt{\Phi_{\text{éch}}+\Phi_{\text{pte}}-2E+eV}\right)$$

Local Tunneling Junction at T > 0K



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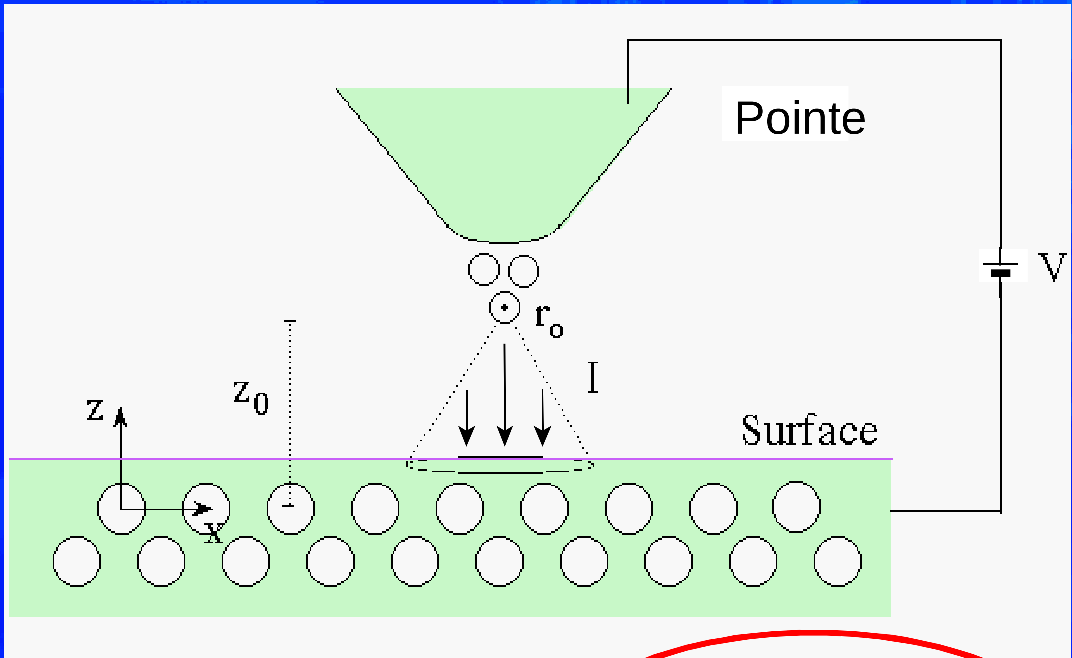
$$I(V,T,x,y,s) \propto e^{-2s\sqrt{\frac{2m_e\Phi}{\hbar^2}}} \times \int_{-\infty}^{\infty} dE\, \rho_{\text{éch}}(E,x,y)\rho_{\text{pte}}(E-eV)\, g(E,V,T)$$

where $g(E,V,T) = f(E-eV,T) - f(E,T)$

If $T = 0$: $\frac{dI}{dV}(V) = -\frac{2\pi e^2 T}{\hbar} N_P\ N_S(eV)$ ⟺ $\rho(\mathbf{r},E) = \sum_k |\psi_k(\mathbf{r})|^2 \delta(E-E_k)$

Local Tunneling Junction at T > 0K



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A. Selloni, et al. … Rev. B 31, 2602 (1985).
N. L… Rev. B 34, 5947 (1986).

STM topography

$$I(V,T,x,y,s) \propto e^{-2s\sqrt{\frac{2m_e\Phi}{\hbar^2}}} \times \int_{-\infty}^{\infty} dE\, \rho_{\text{éch}}(E,x,y)\rho_{\text{pte}}(E-eV)\, g(E,V,T)$$

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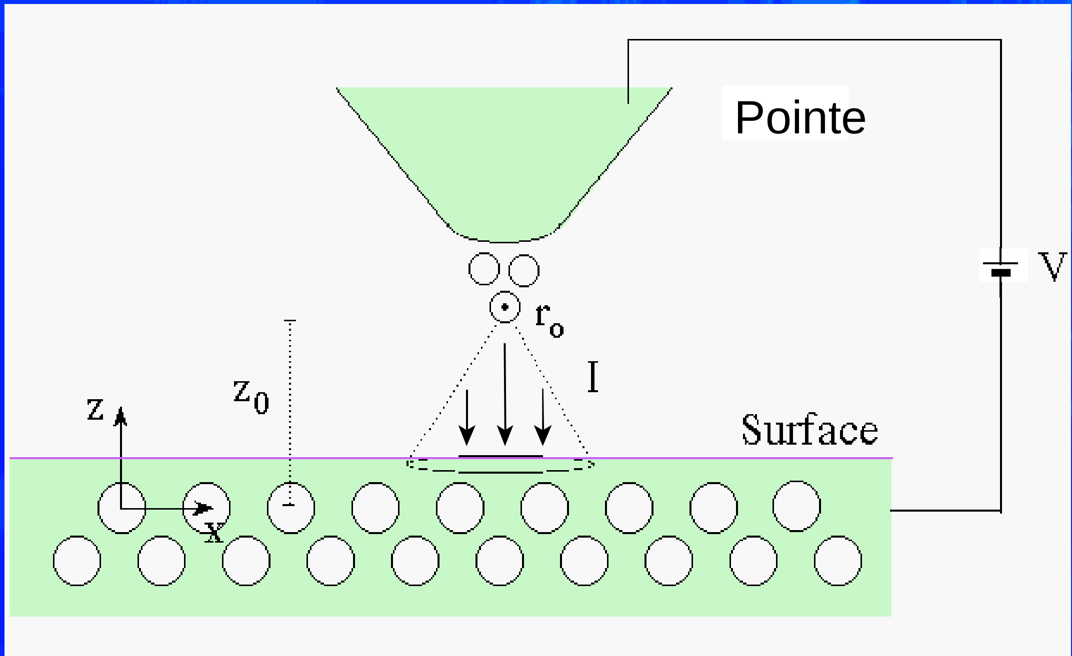
Local Tunneling Junction at T > 0K



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A. Selloni, et al. Phys. Rev. B 31, 2602 (1985).

N. Lang, Phys. Rev. B 34, 5947 (1986).

$$I(V,T,x,y,s) \propto e^{-2s\sqrt{\frac{2m_e\Phi}{\hbar^2}}} \times \int_{-\infty}^{\infty} dE\, \rho_{\text{éch}}(E,x,y) \cdots - eV)\, g(E,V,T)$$

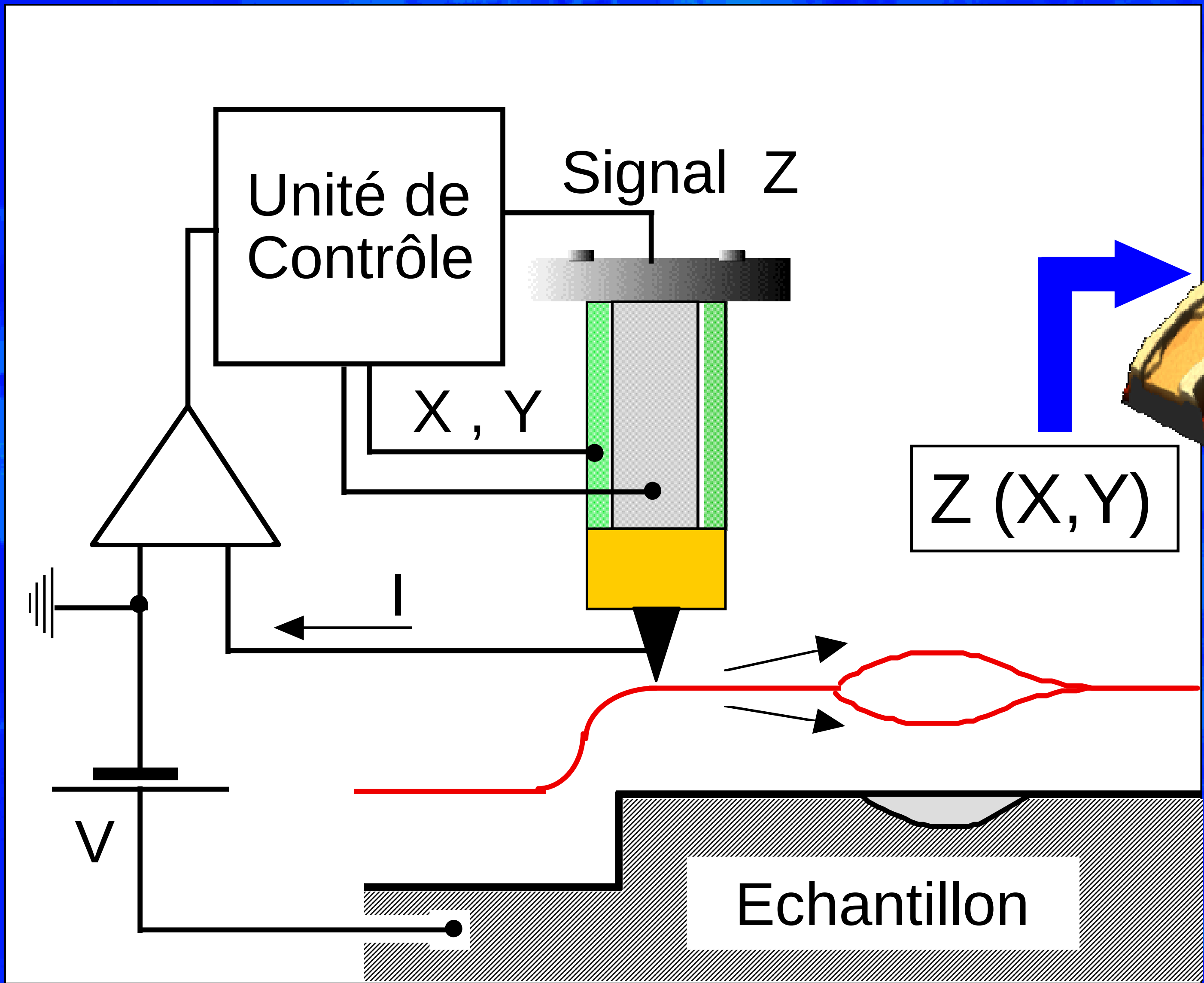
STS Spectroscopy

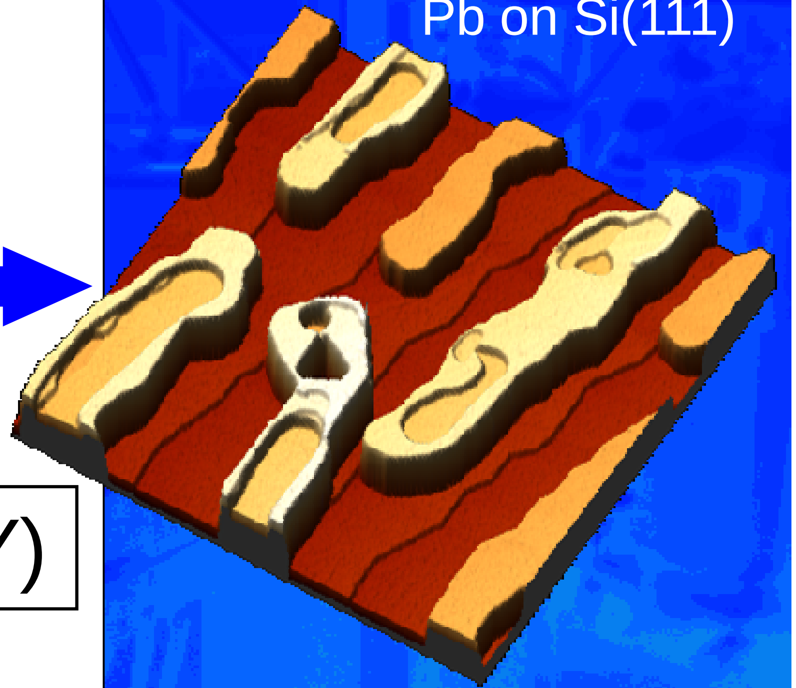
where $g(E,V,T) = f(E-eV,T) - f(E,T)$

If $T = 0$: $\frac{dI}{dV}(V) = -\frac{2\pi e^2 T}{\hbar} N_P\ N_S(eV)$

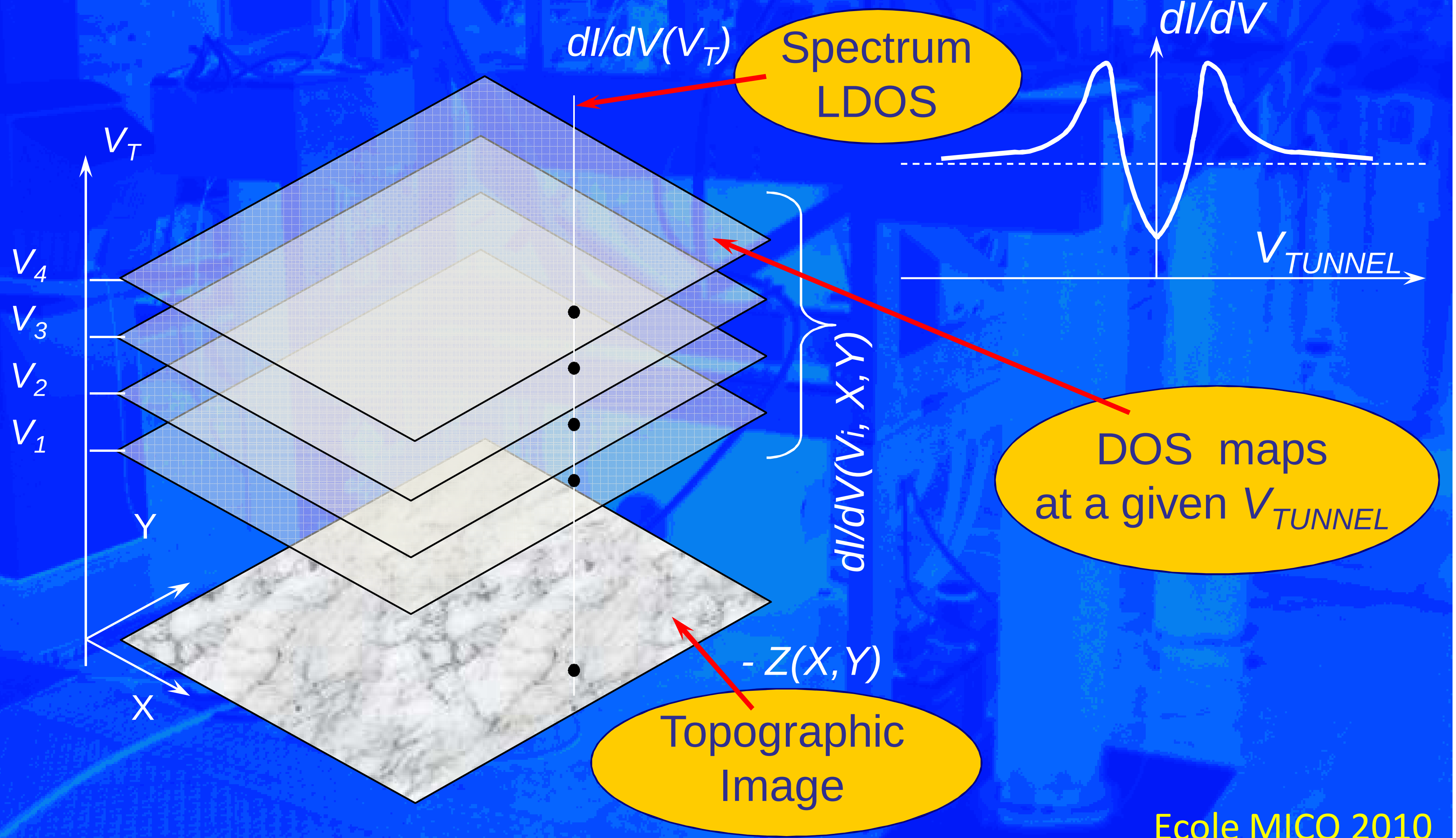
$$\rho(\mathbf{r},E) = \sum_k |\psi_k(\mathbf{r})|^2\, \delta(E-E_k)$$

STM: Working principle





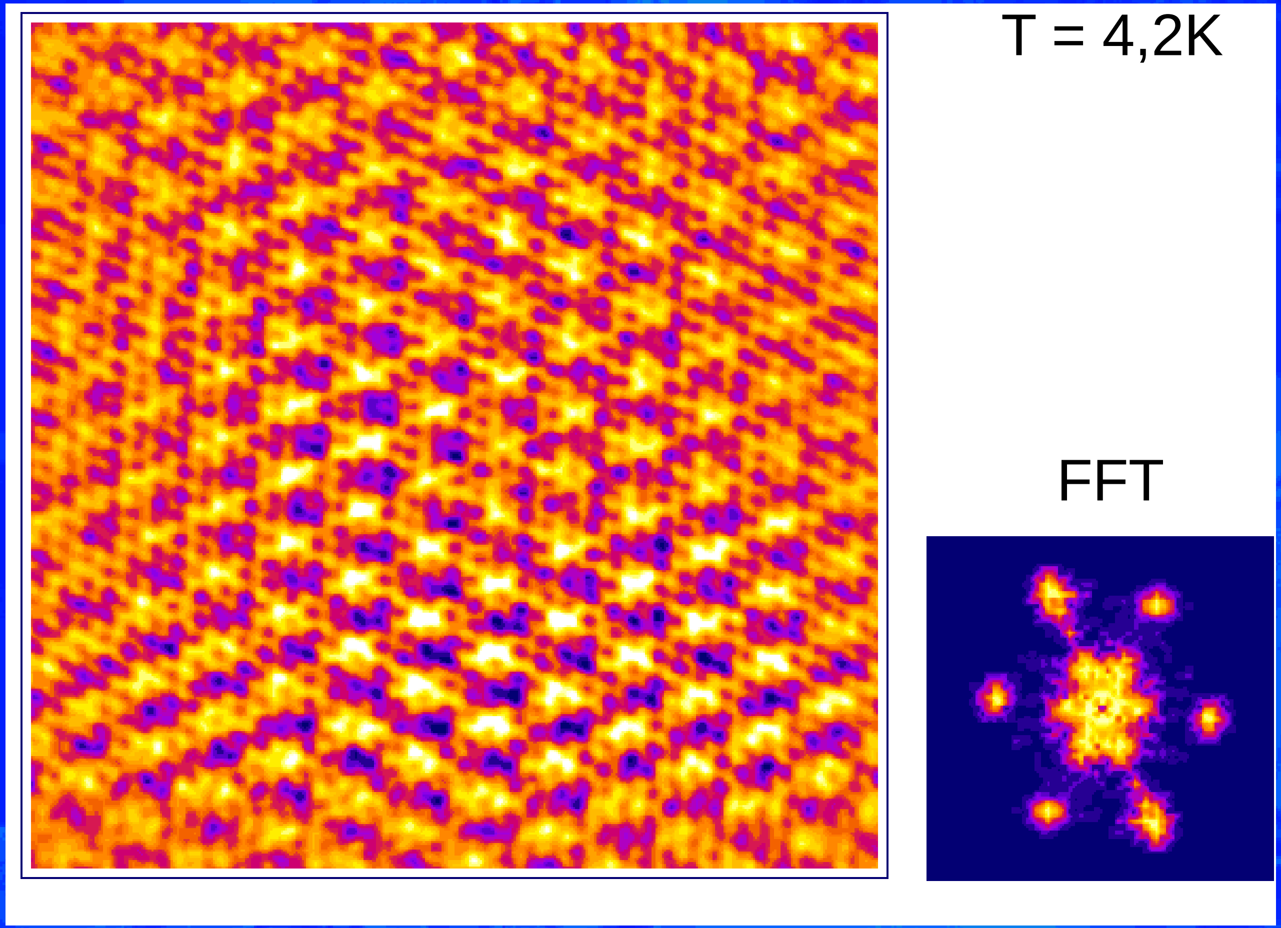
STM/STS :
Scanning Tunneling Spectroscopy



STS: Charge Density Waves in $NbSe_2$

T_{ODC} = 33K

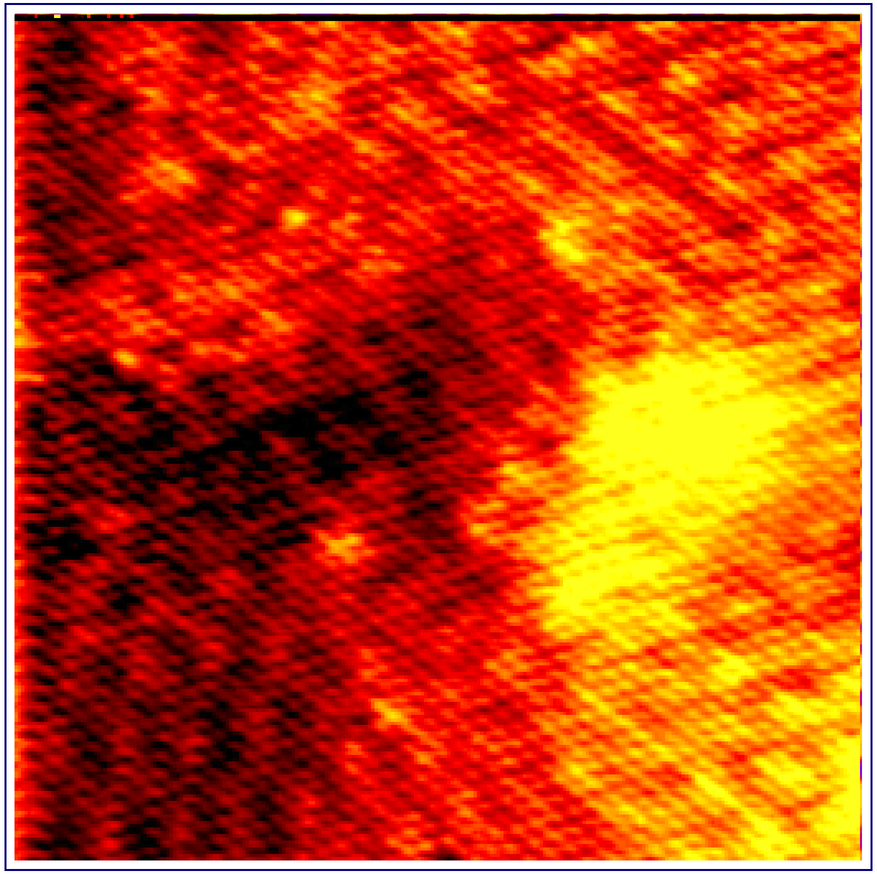
Topographic STM Image13nm x 13 nm



STS: Charge Density Waves in $NbSe_2$

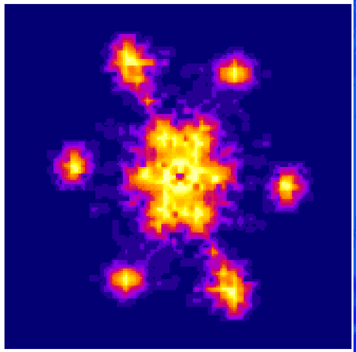
TODC = 33K

Topographic STM Image18nm x 18 nm

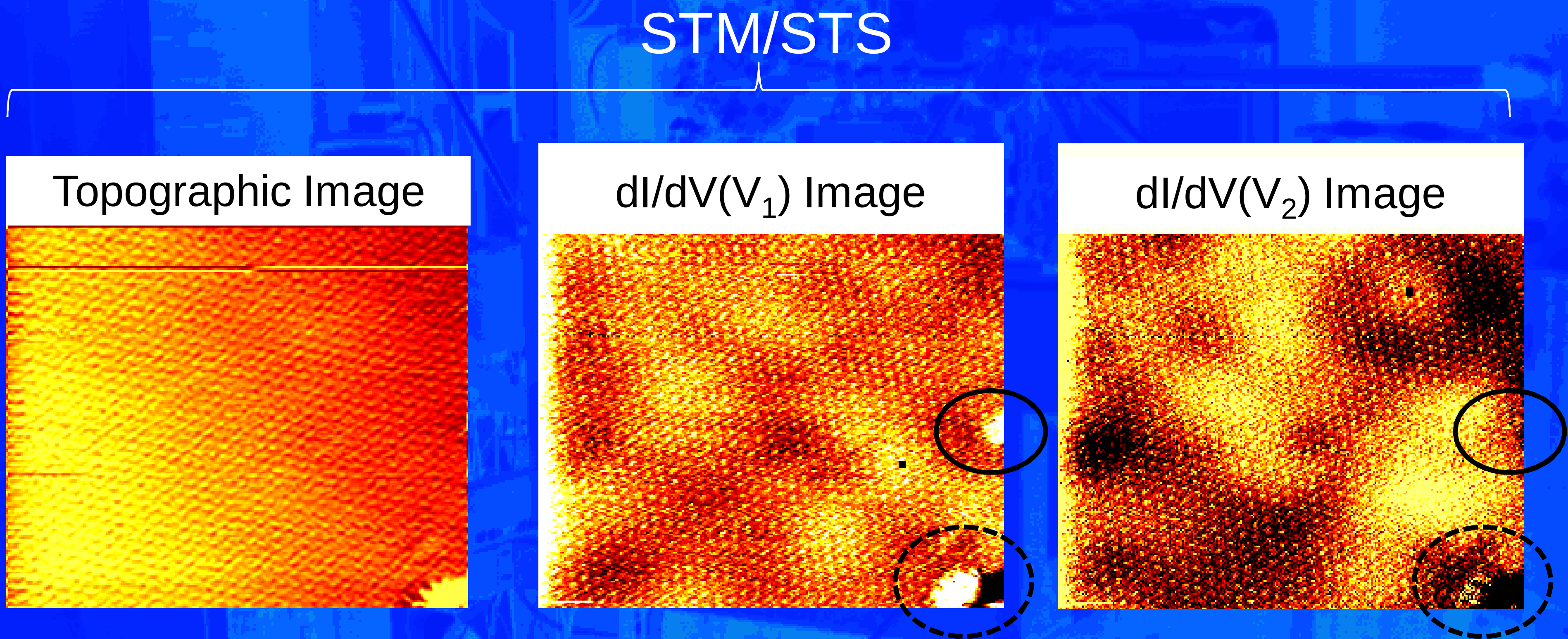


T = 4,2K

FFT



STS: Charge Density Waves in $NbSe_2$



T. Cren, D. Roditchev, W. Sacks (1995-2000)

N.B. Charge Density Waves are strongly perturbed by local disorder (the defects lying under surface are detectable !)

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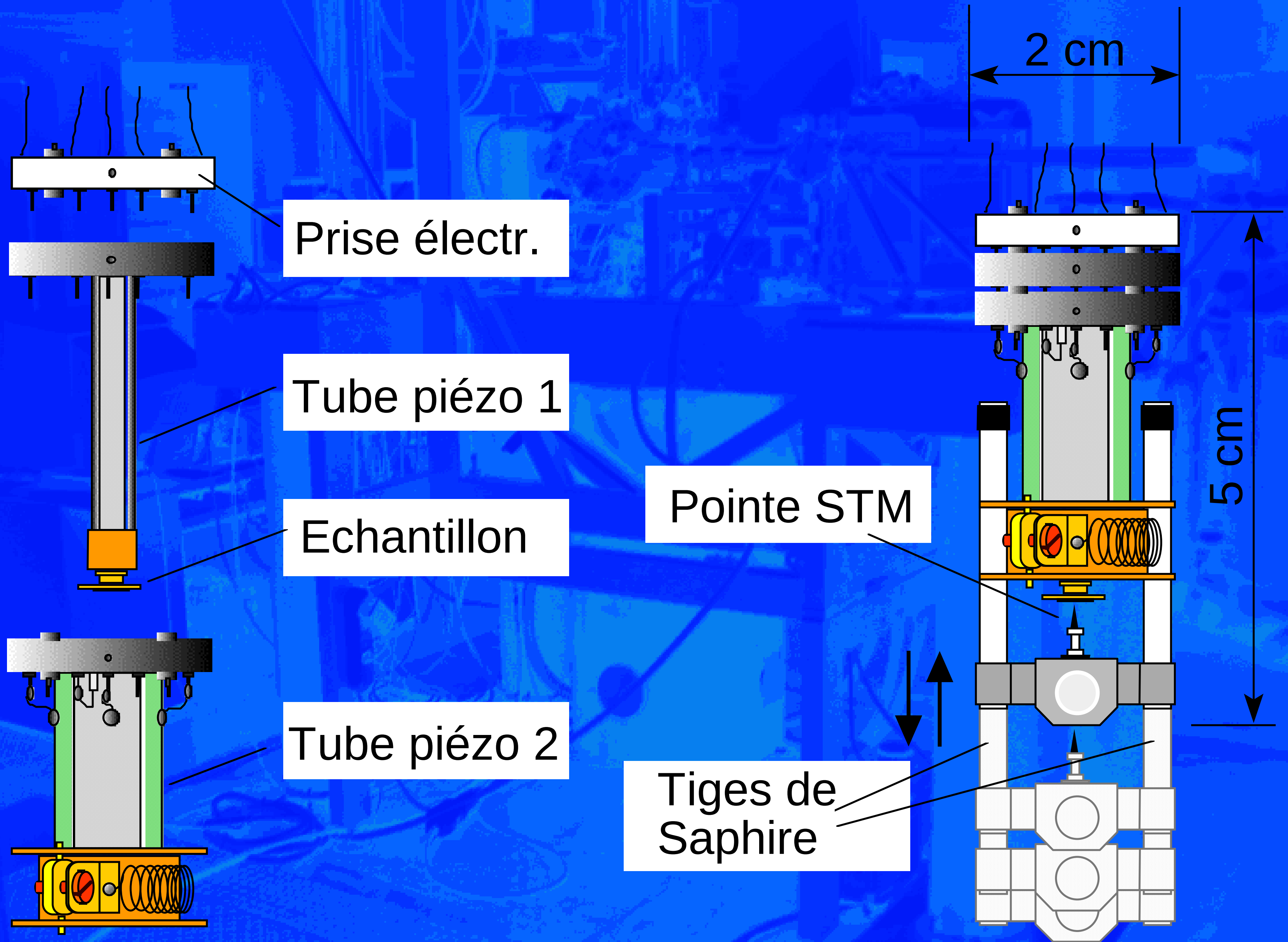
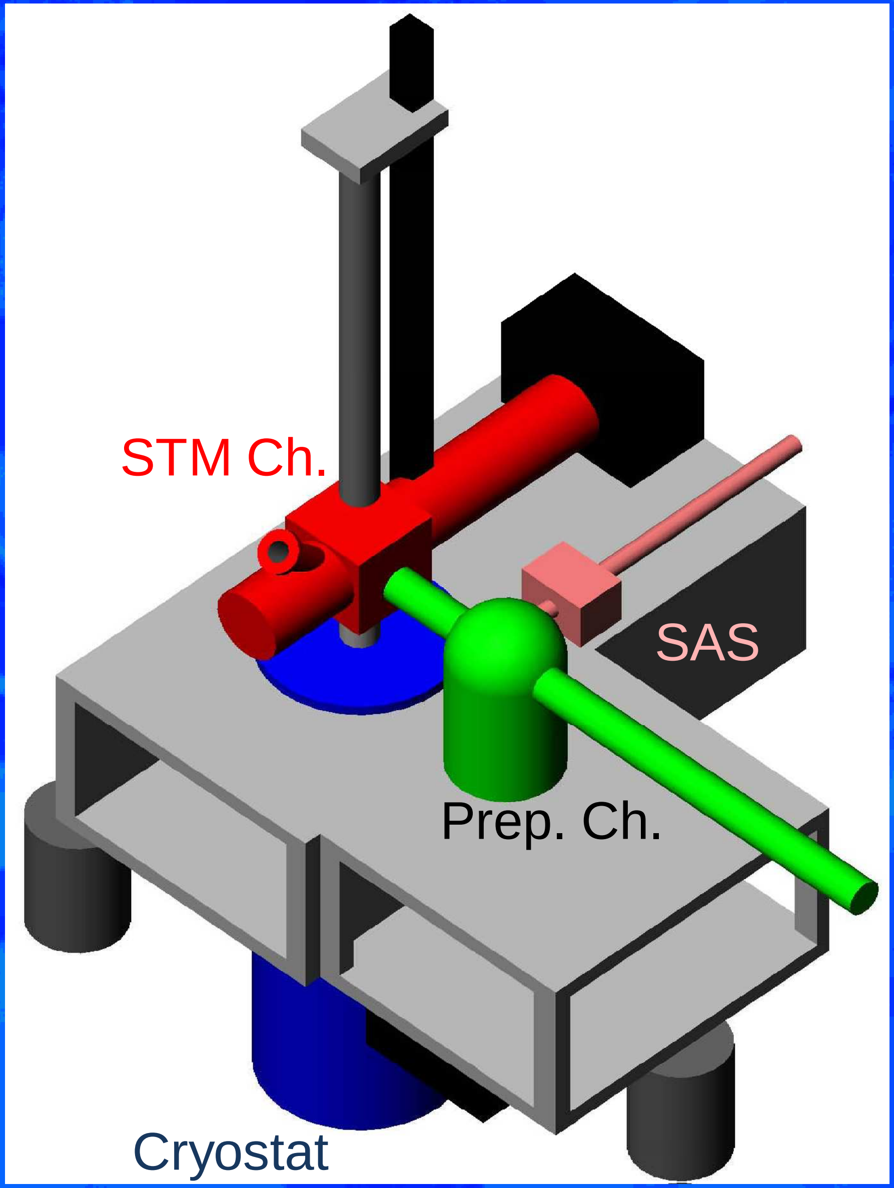

2 cm
Prise électr.
Tube piézo 1
Echantillon
Tube piézo 2
Pointe STM
5 cm
Tiges de
Saphire

Microscope tunnel fonctionnant à l'air

« Easy-Scan »

commercialisé par la société Schaefer Techniques, prix <10.000 E

Scanning Tunneling Microscopy and Spectroscopy at INSP in Paris



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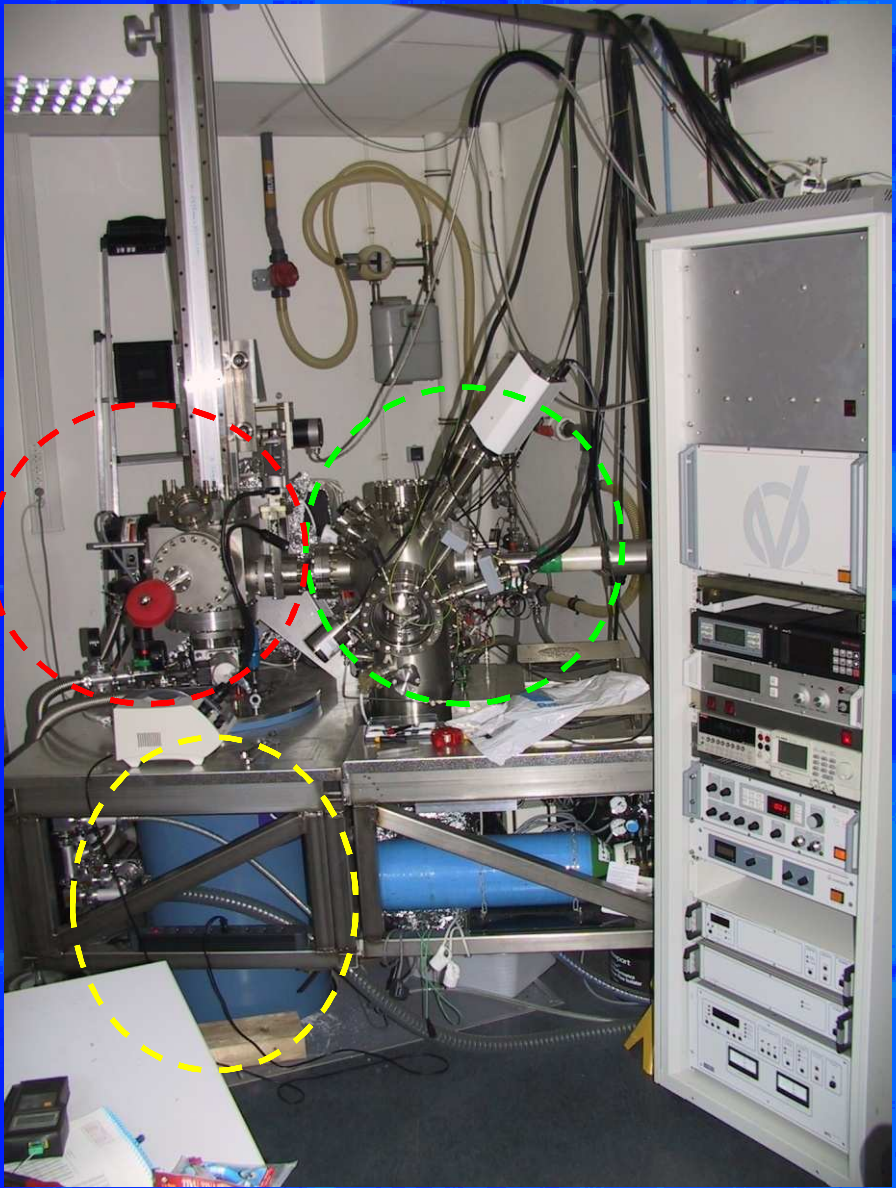

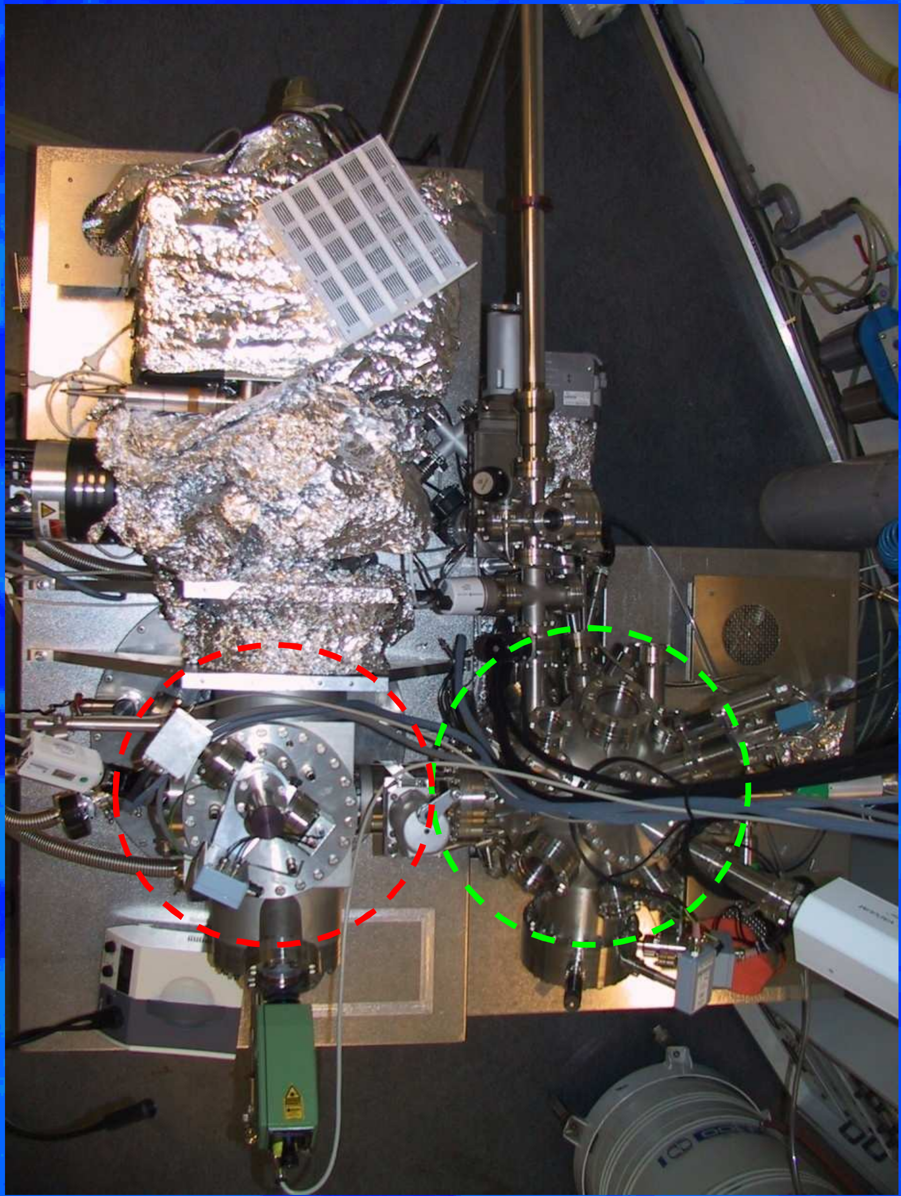

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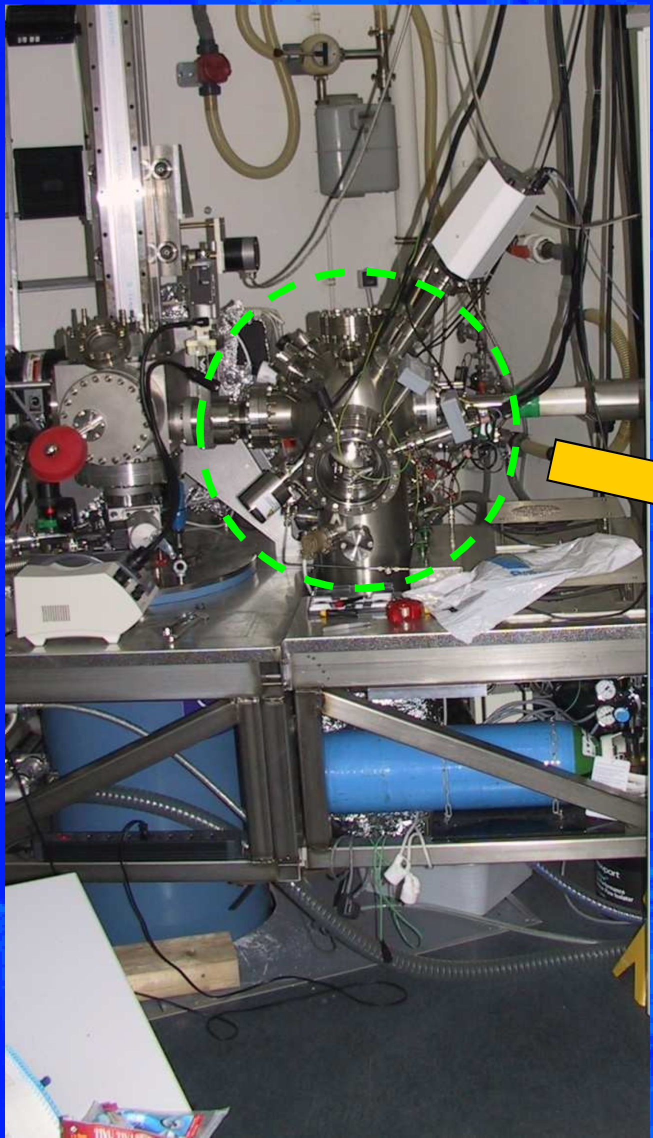
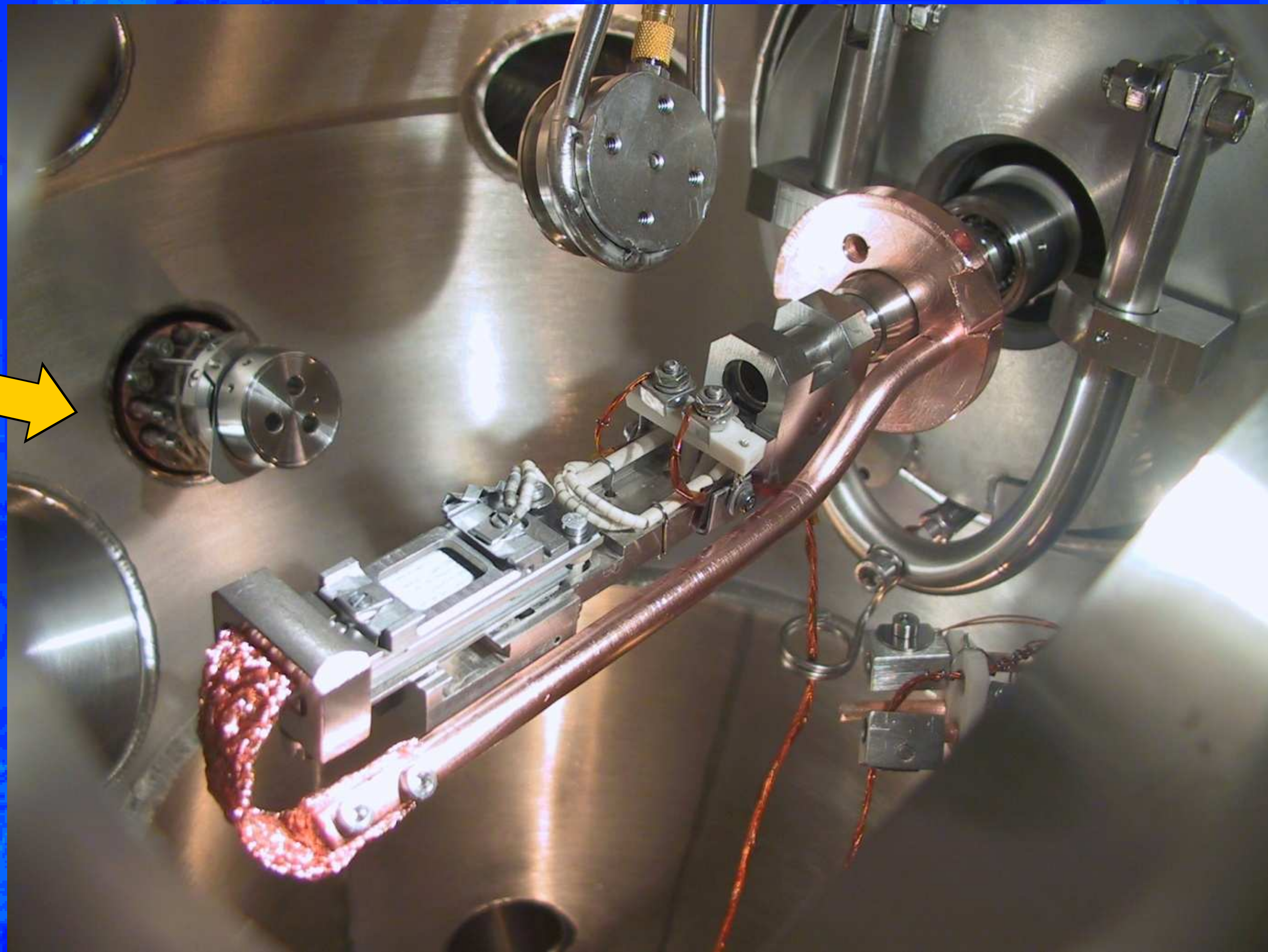
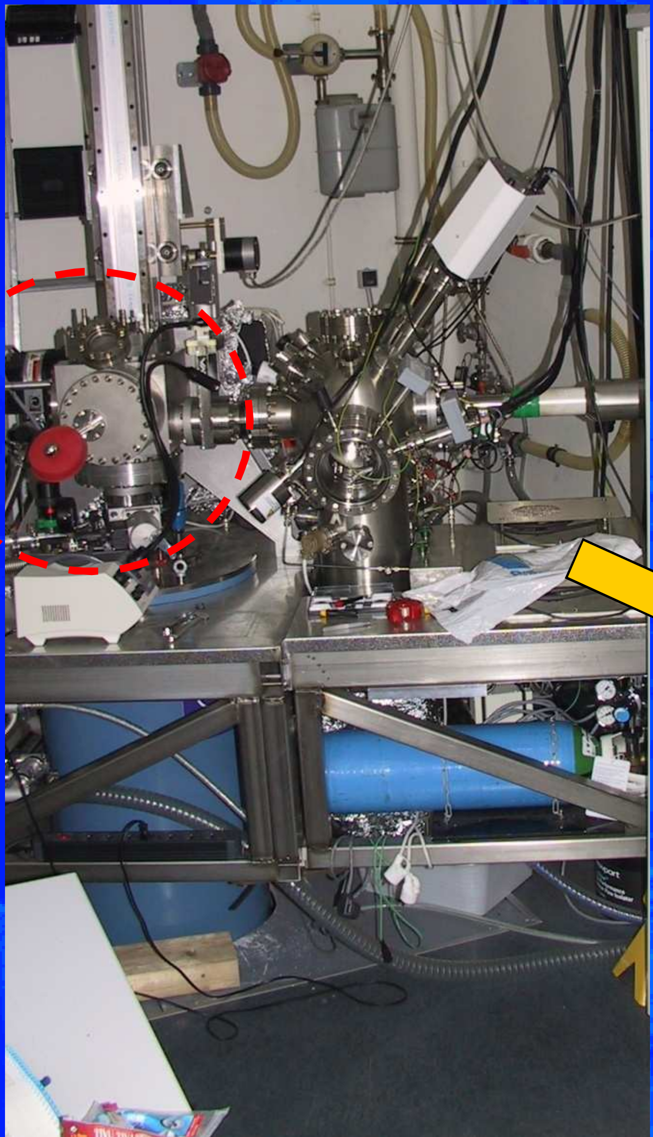


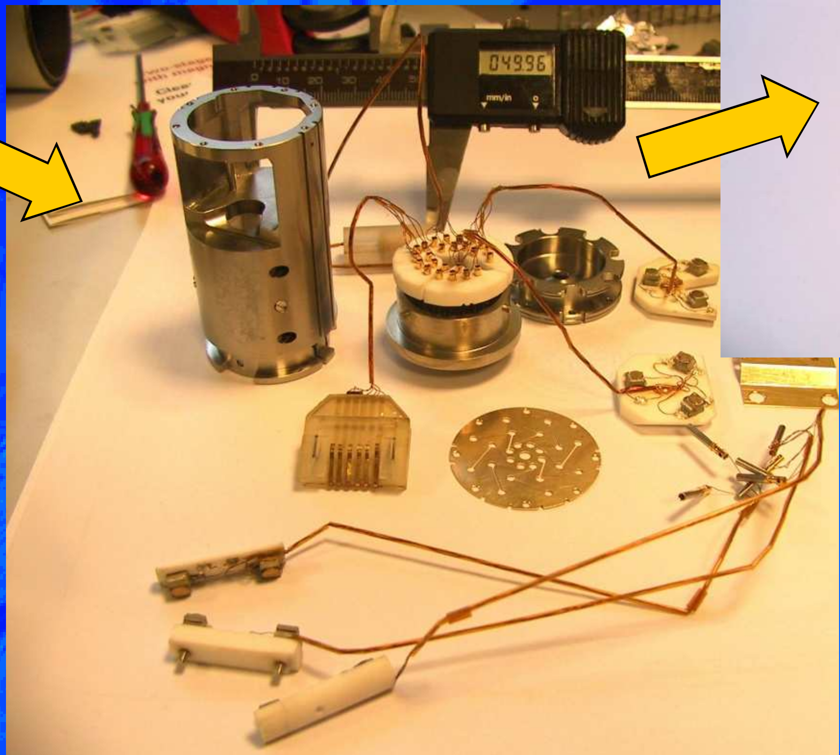
Electron Beam Deposition under UHV

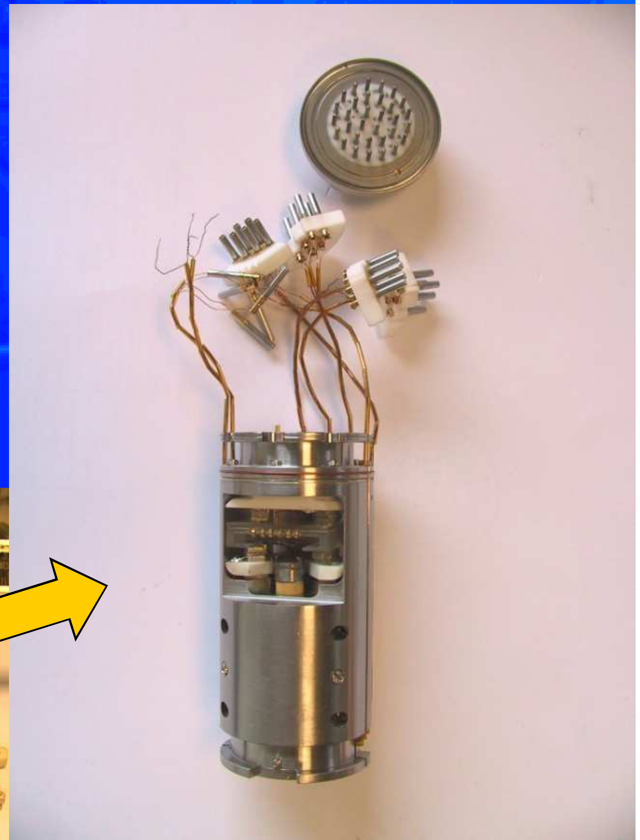


Scanning Tunneling Microscopy and Spectroscopy at INSP in Paris

A new STM Head







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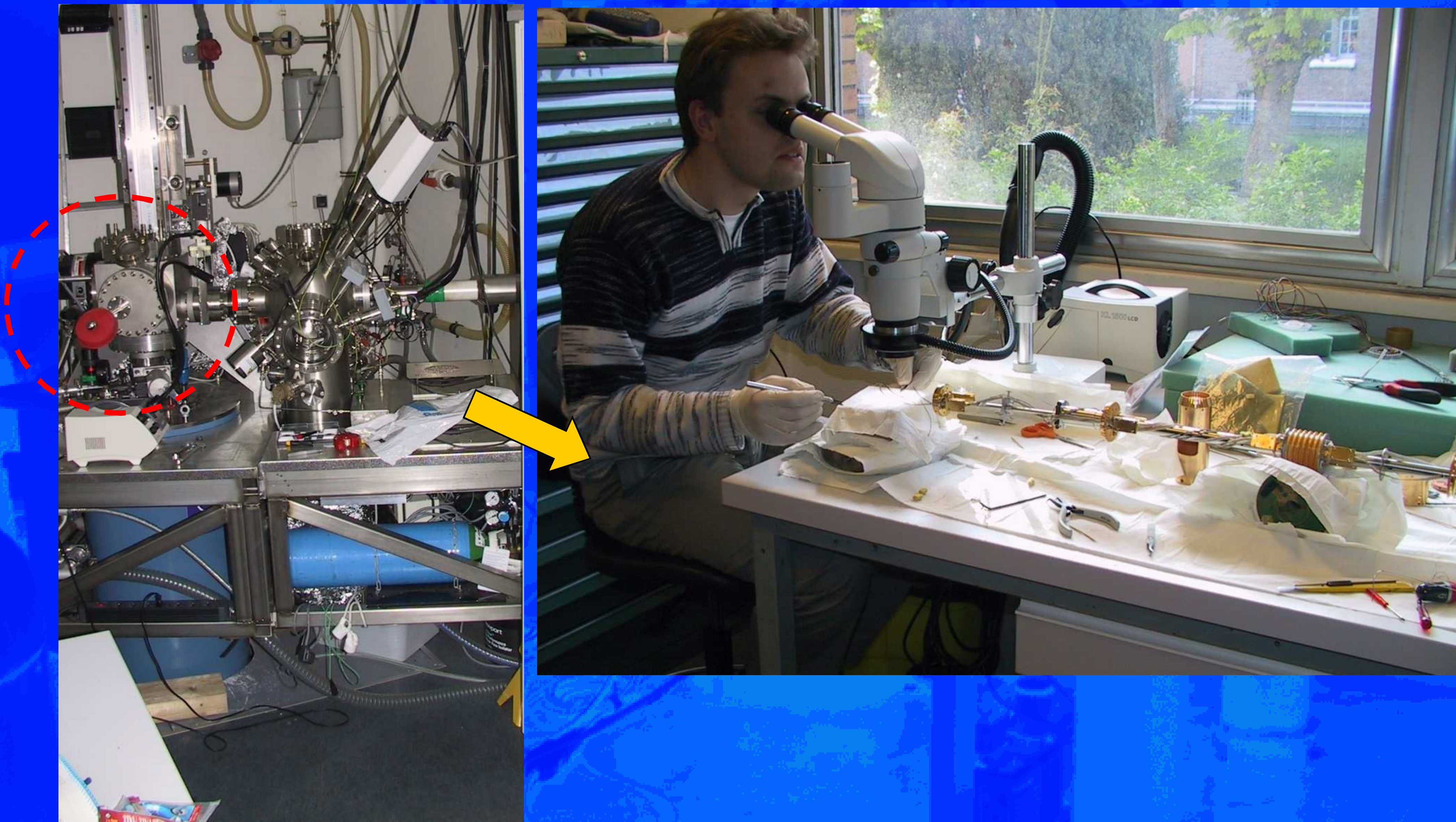

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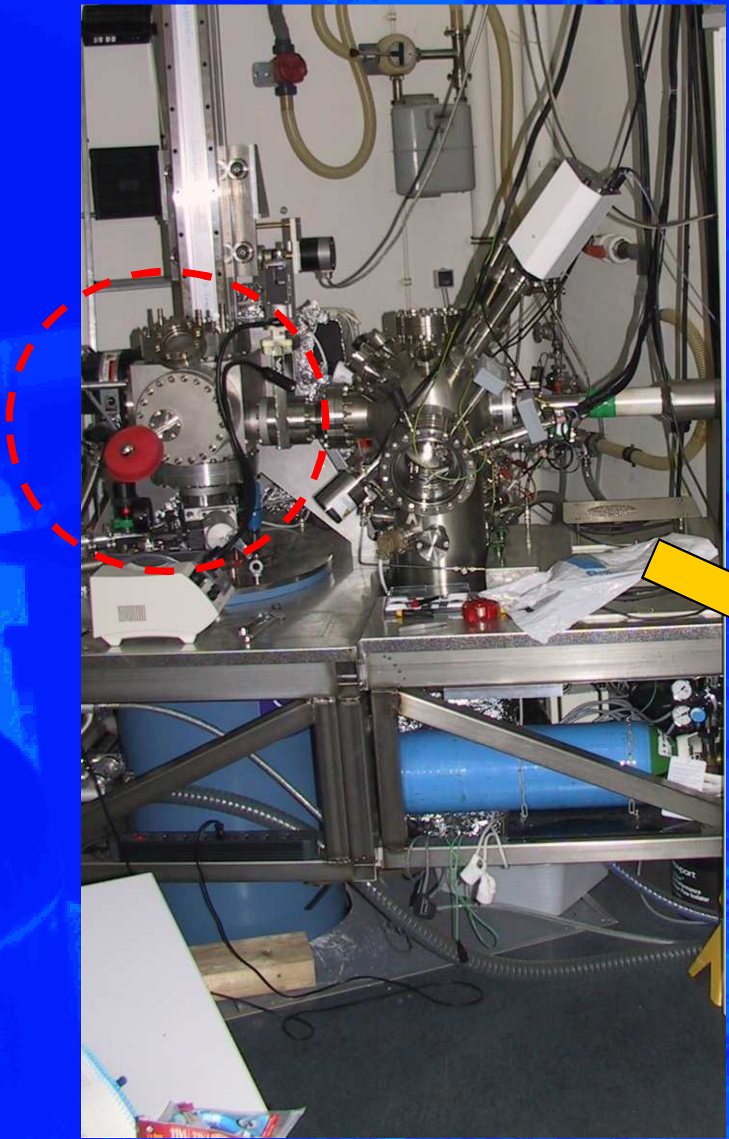
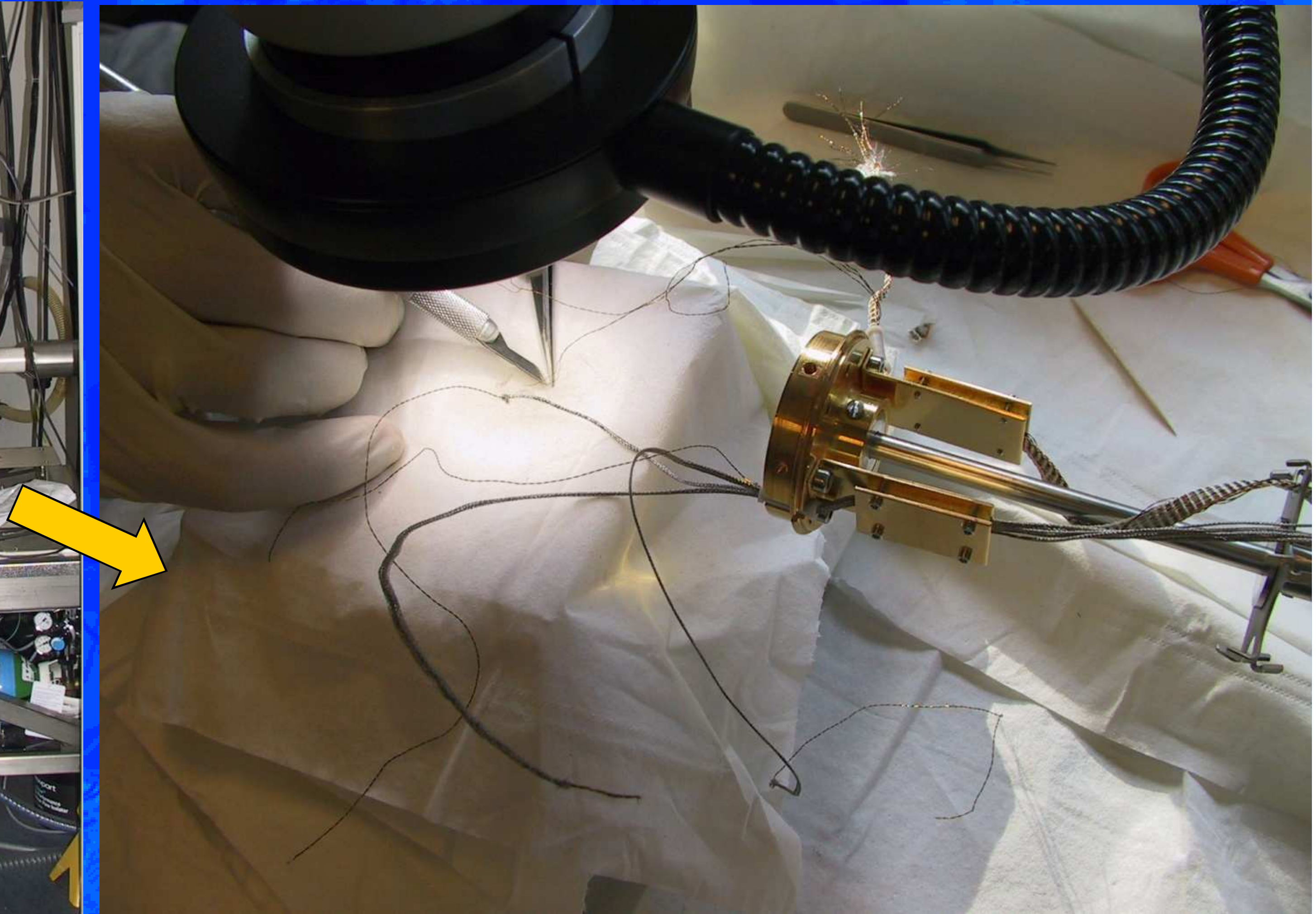
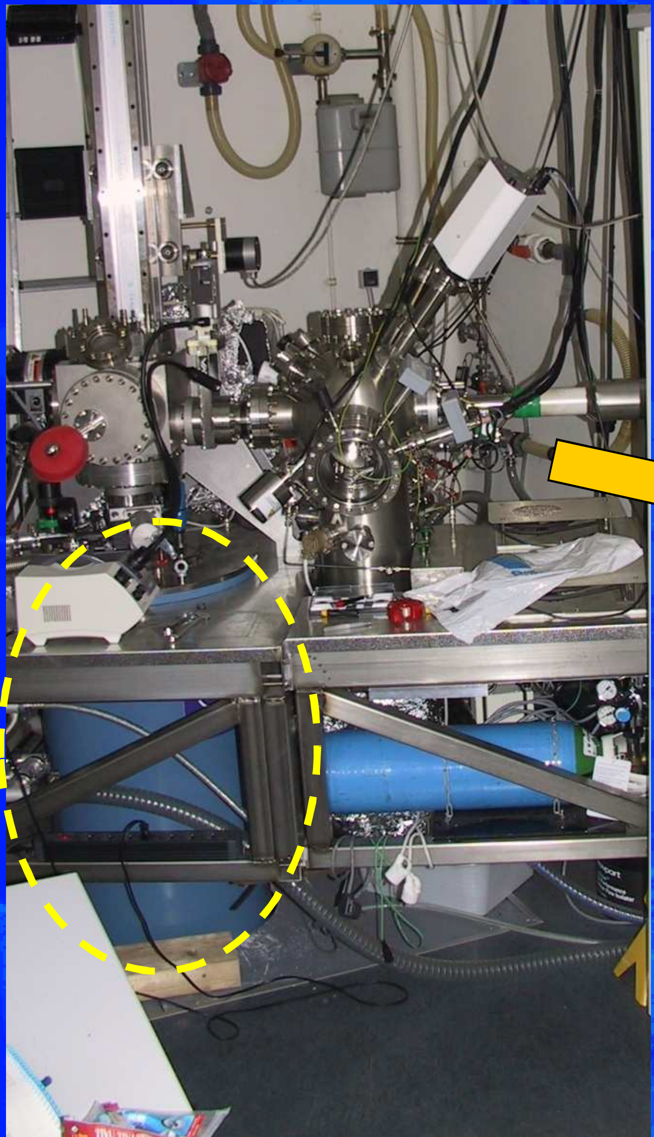




Scanning Tunneling Microscopy and Spectroscopy at INSP in Paris

Ultra-Low Temperatures 0.3K
Magnetic Field up to 10Tesla



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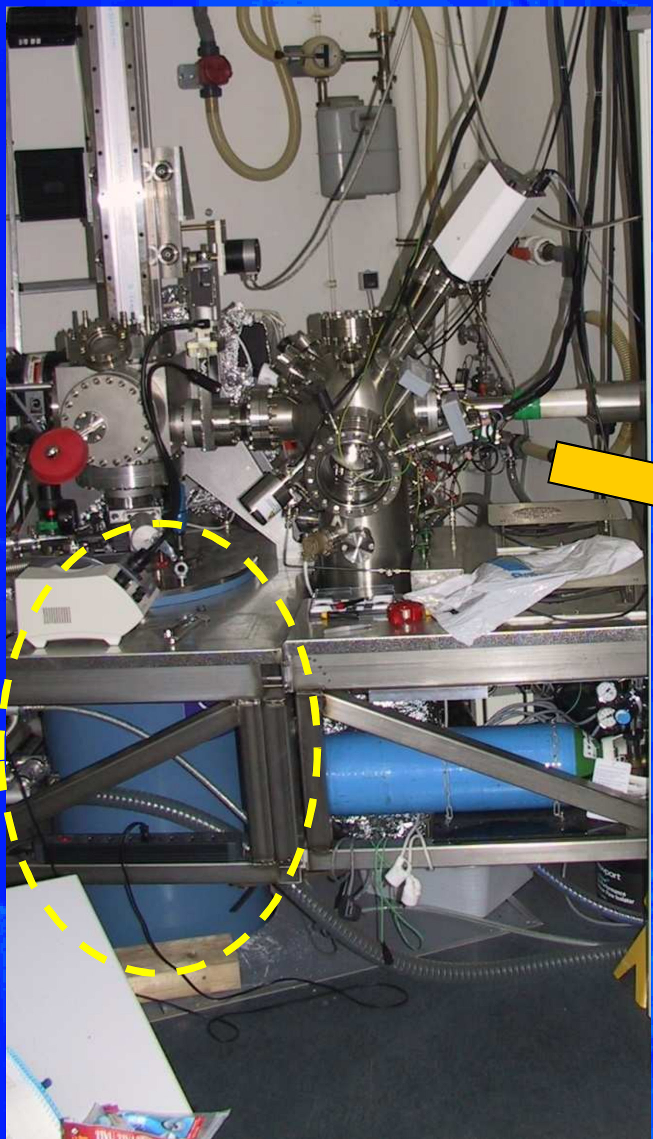
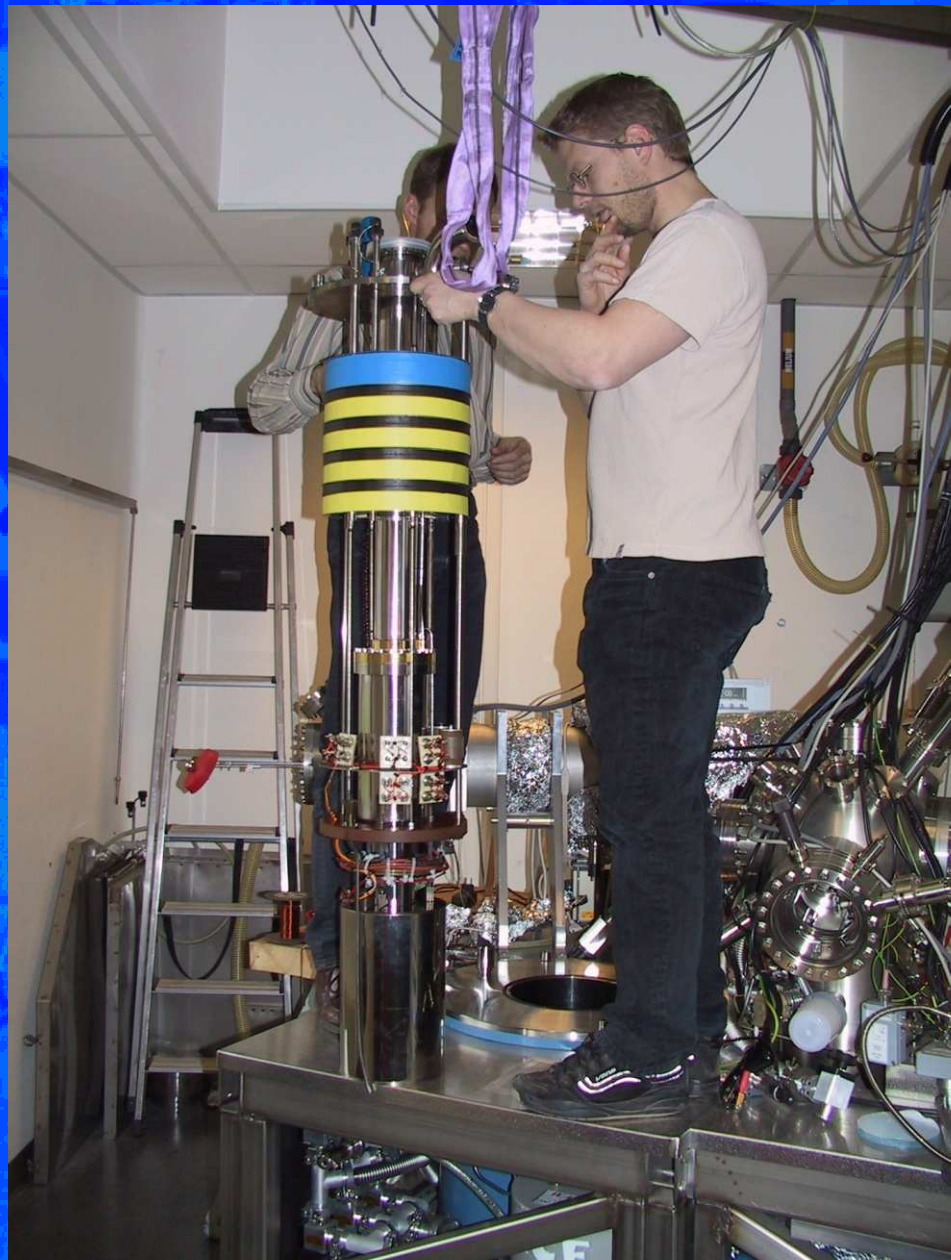
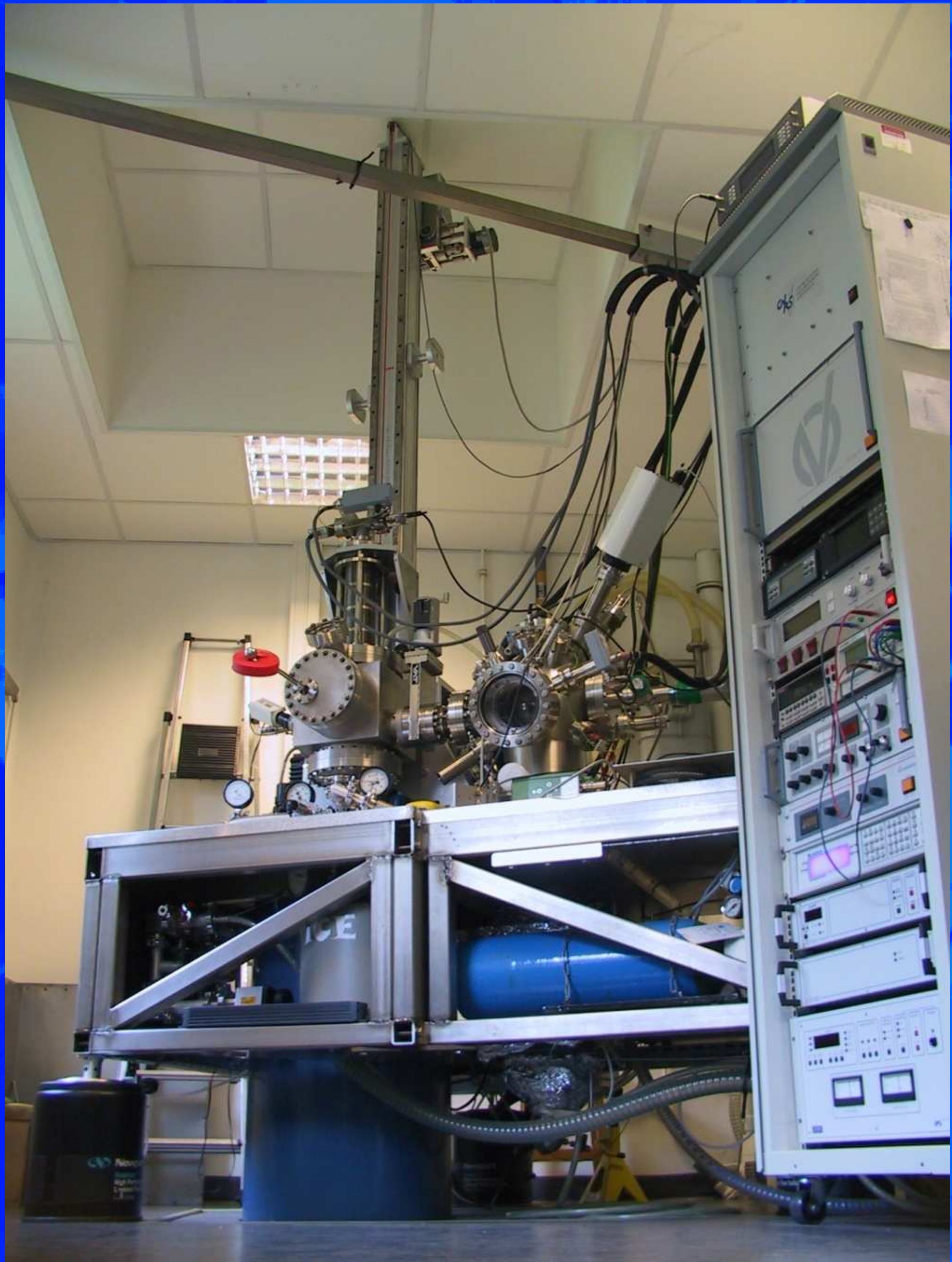




Scanning Tunneling Microscopy and Spectroscopy at INSP in Paris



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Superconductivity: Ginzburg-Landau Approach

Superconducting phase is described by macroscopic wave function:

$$\Psi = |\Psi| \exp(i\varphi)$$

$$n_s = |\Psi(\vec{r})|^2$$

Two equations:

$$\frac{1}{2m^\star}(-i\hbar\vec{\nabla} - 2e\vec{A})^2\Psi + \beta|\Psi|^2\Psi = -\alpha\Psi \quad (1)$$

$$\vec{j} = \frac{2e}{m^\star}|\Psi|^2(\hbar\vec{\nabla}\varphi - 2e\vec{A}) = 2e|\Psi|^2\vec{v}_s \quad (2)$$

where $\vec{v}_s = (\hbar\vec{\nabla}\varphi - 2e\vec{A})/m^\star$

Boundary condition at the sample edge:

$$(-i\hbar\vec{\nabla} - 2e\vec{A})\Psi\Big|_\perp = 0$$

Superconductivity: Ginzburg-Landau Approach

Integrating the 2nd G-L equation over an area *S*:

$$\oint m^* \vec{v}_s . \vec{ds} = \hbar \oint \vec{\nabla} \varphi . \vec{ds} - 2e \oint \vec{A} . \vec{ds}$$

where $\oint \vec{A} . \vec{ds} = \Phi$, Φ being the magnetic flux crossing *S*

Condition on the phase φ (since ψ is a single-valued function):

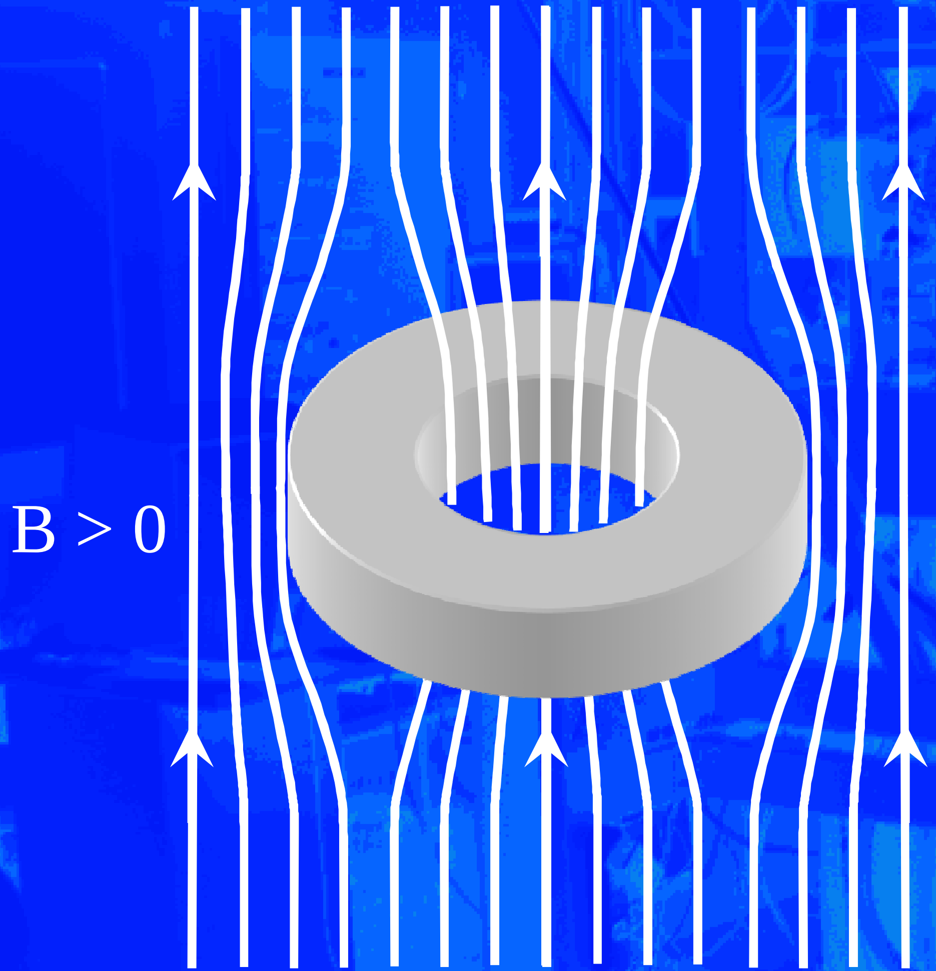
$$\oint \vec{\nabla} \varphi . \vec{ds} = n 2\pi .$$

Fluxoid quantification:

$$\Phi' = \Phi + \frac{1}{2e} \oint m^* \vec{v}_s . \vec{ds} = n \frac{h}{2e} = n \Phi_0$$

where Φ_0 is the flux quantum: $\Phi_0 = \frac{h}{2e} = 2.07 \cdot 10^{-15} \ \mathrm{Tm}^2$

Superconductivity: Ginzburg-Landau Approach



$$\Phi' = \Phi + \frac{1}{2e}\oint m^* \vec{v}_s . \vec{ds} = n\frac{h}{2e} = n\Phi_0$$

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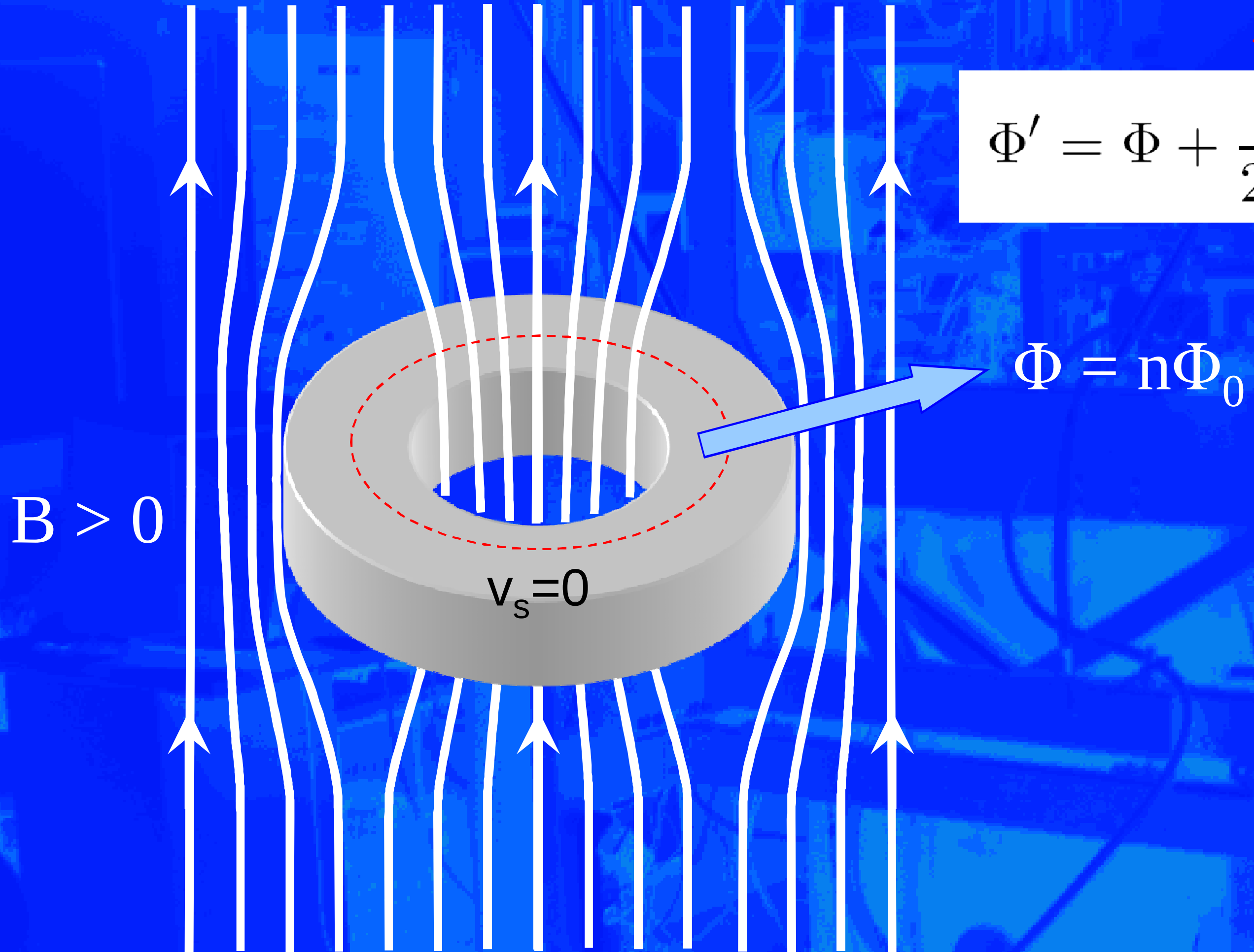

Superconductivity: Ginzburg-Landau Approach

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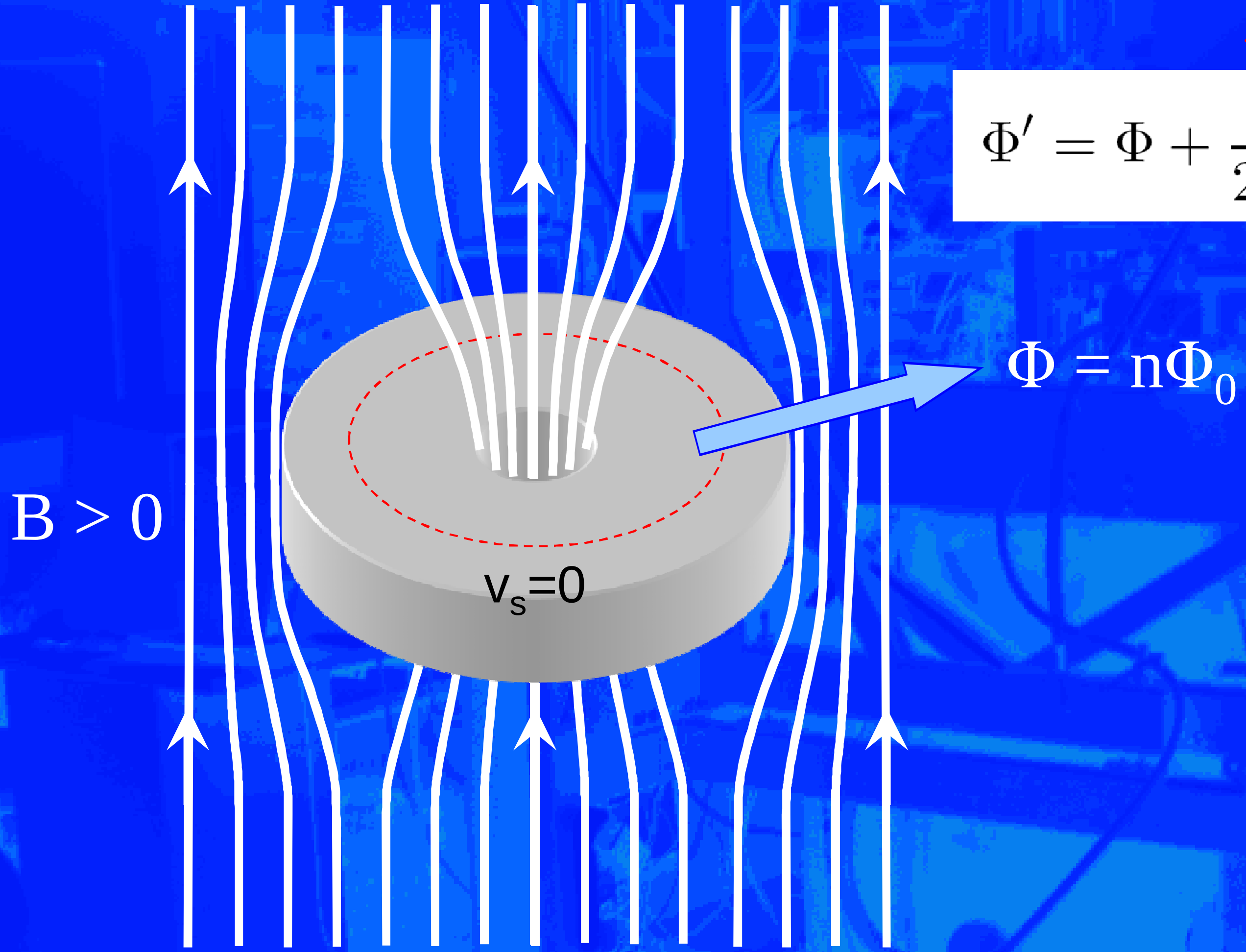

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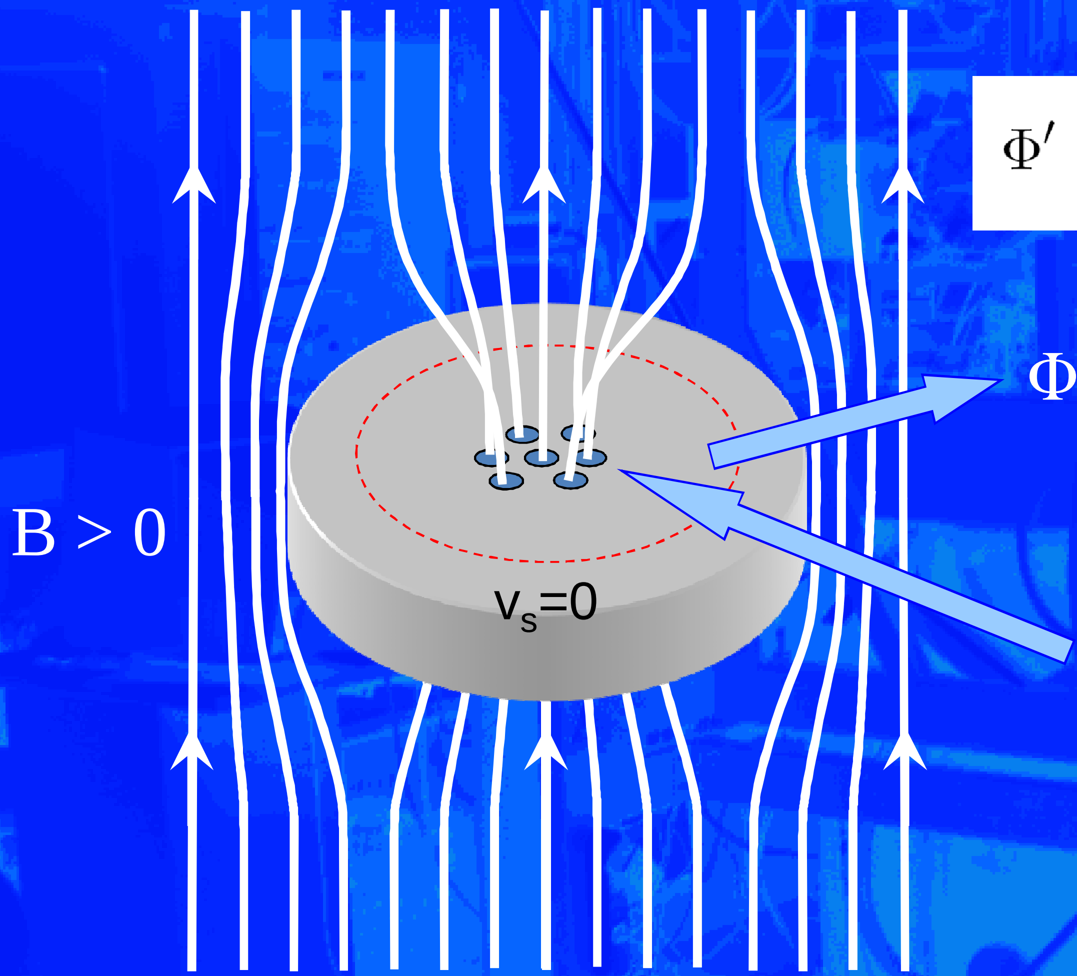


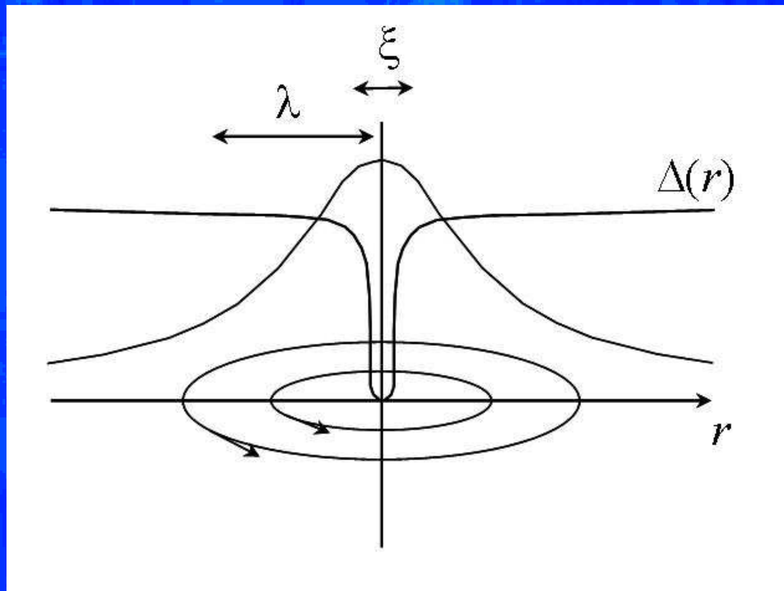
$$\Phi' = \Phi + \frac{1}{2e}\oint m^* \vec{v}_s . \vec{ds} = n\frac{h}{2e} = n\Phi_0$$

$\Phi = n\Phi_0$

In type II superconductors (k>1) the Abrikosov vortex lattice forms, each vortex containing the flux quantum Φ_0

Superconductivity: Ginzburg-Landau Approach

Vortex Matter in Superconductors
(*very huge field of research*!)



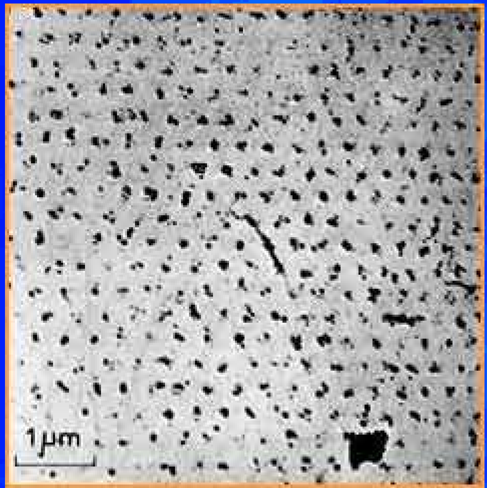
➡ N.B.1 : At the distance *r* $|\vec{\nabla}\varphi| = 1/r$ ➡ it diverges at *r* = 0 $(v_s \rightarrow \infty)$

➡ N.B.2 : Flux quantification is valid over the area $S >> \pi\lambda^2$

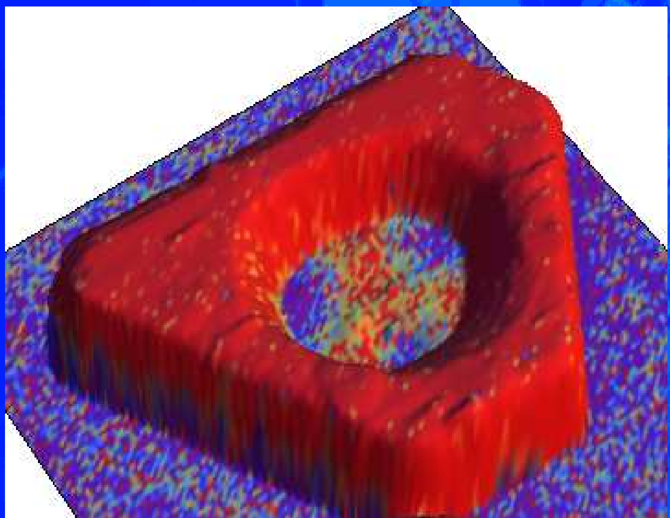
Vortex: General Property of Rotating Quantum Condensates

Superconductors (BCS)

First image of Vortex, 1967

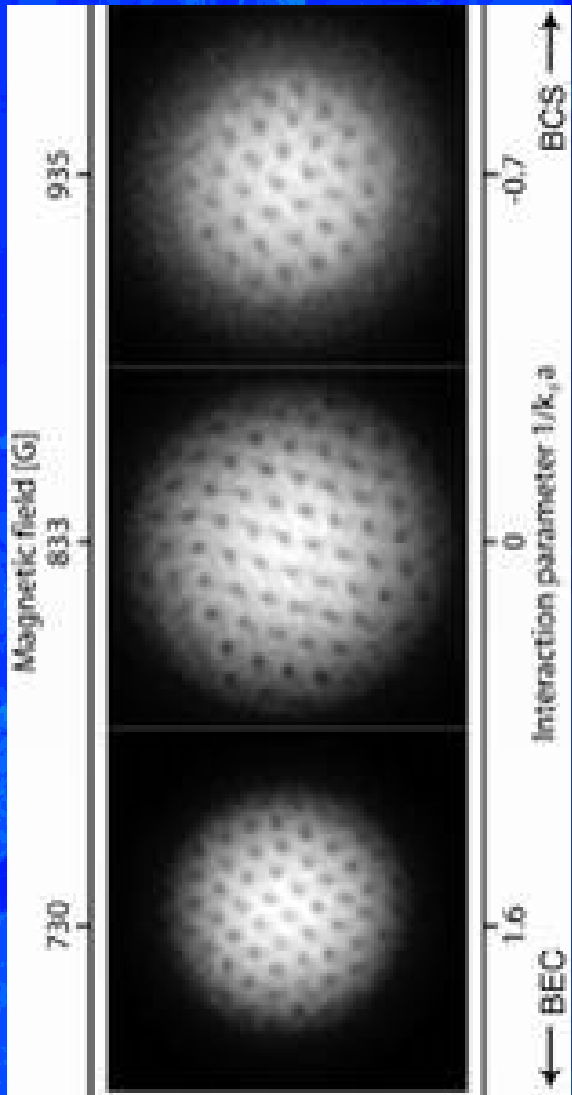


3 vortices in SC nano-island
STM/STS, INSP, 2009



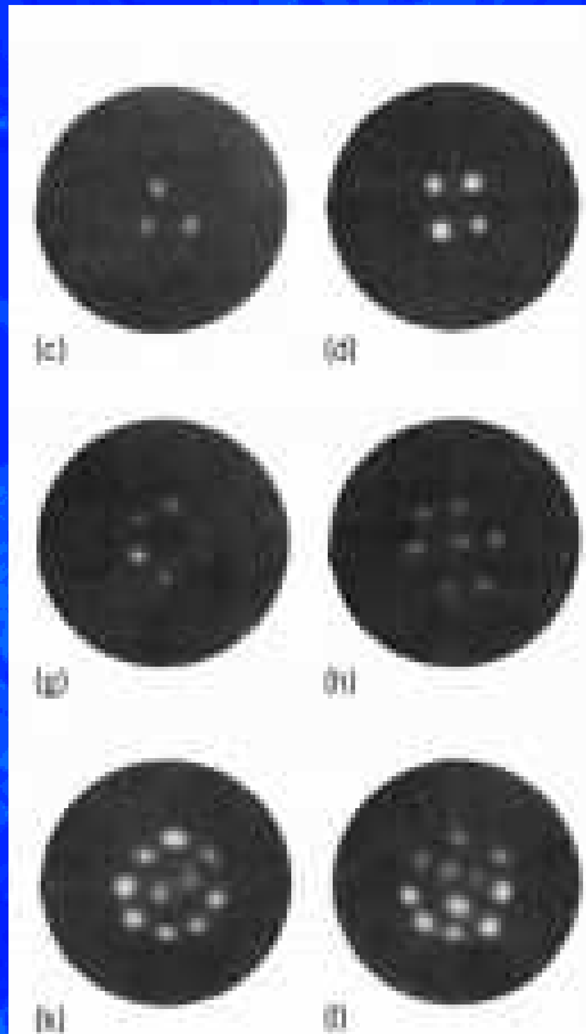
Cold atoms (BEC)

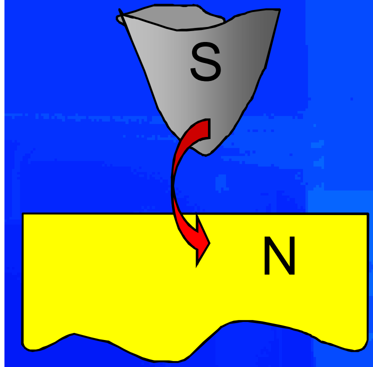
Vortex in ultracold condensate of atoms



Quantum liquids

Vortex in superfluid He





Tunneling into a Superconductor

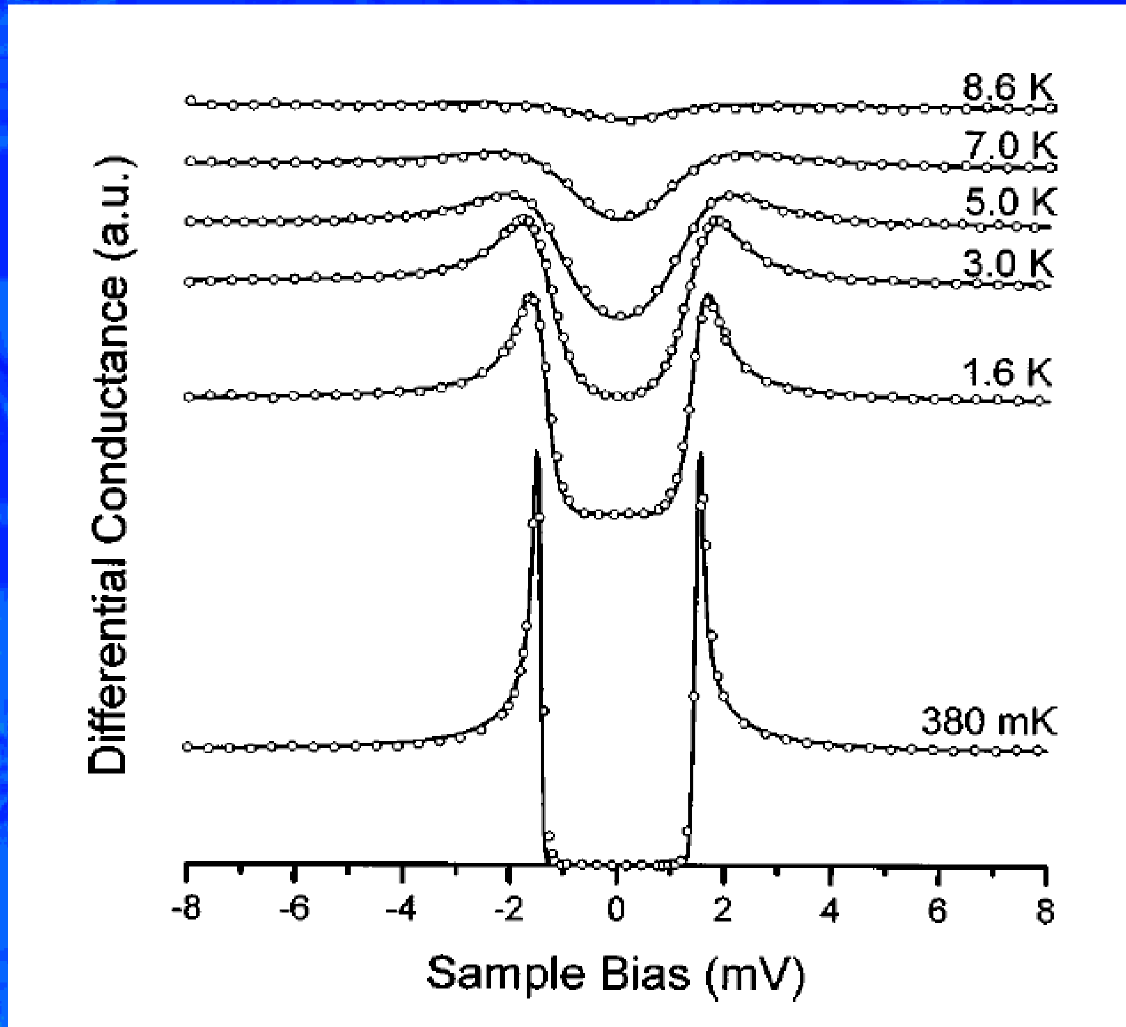
$$\frac{dI}{dV}(V) = -\frac{2\pi e^2 T}{\hbar} N_p \int_{-\infty}^{\infty} N_S(E+eV)\ \frac{\partial f}{\partial E}(E)\, dE$$

BCS-kind Superconductor:
Gap 2Δ in the excitation spectrum:

$$N_s(E) = N(0)\frac{E}{\sqrt{(E^2 - \Delta^2)}}$$

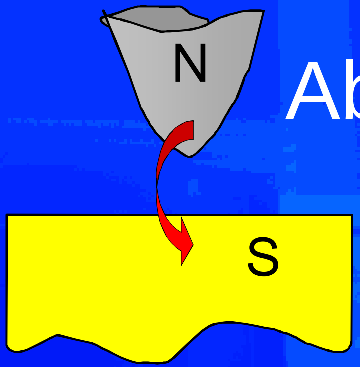
BCS

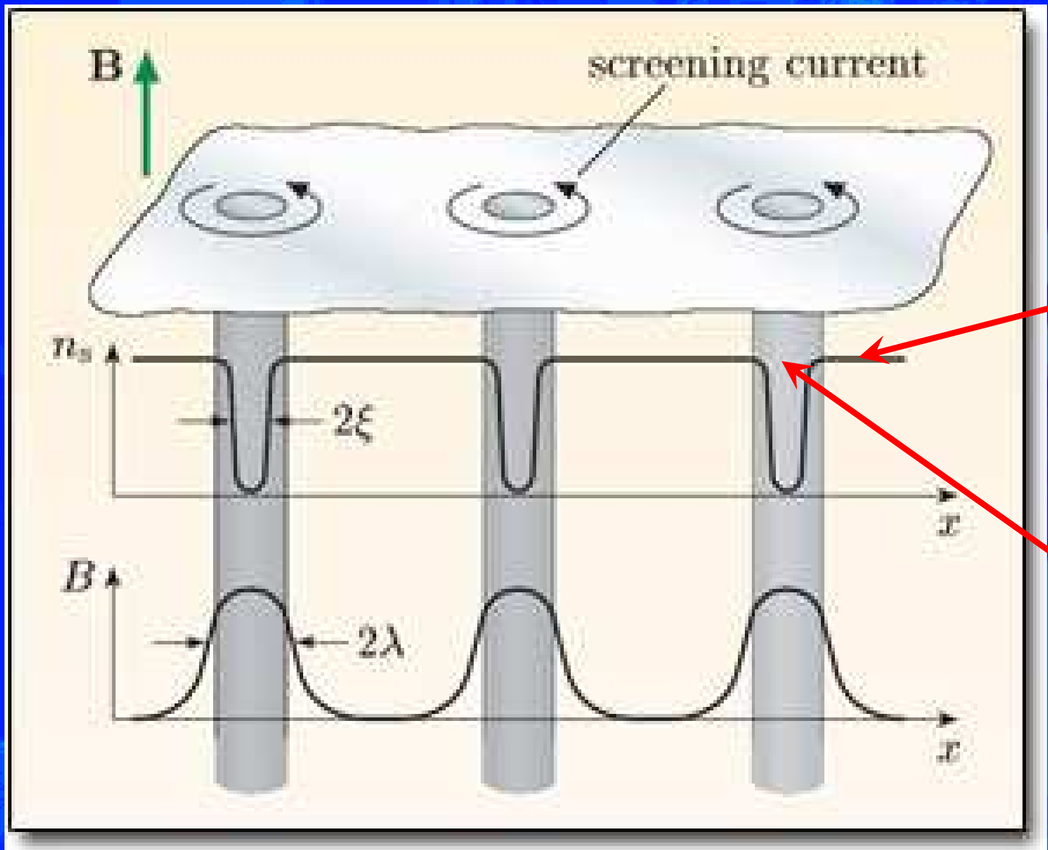
$$\frac{2\ \Delta(0)}{k\ T_c} \approx 3.5$$

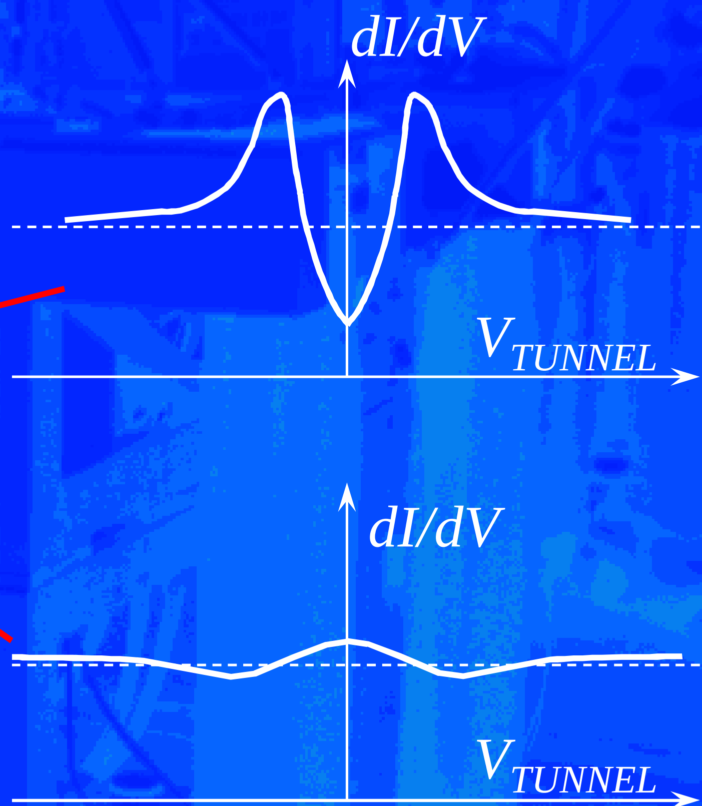


Pan, Davis, Univ. de Berkeley.(APL,1998)

Abrikosov Vortex Lattice observed by Scanning Tunneling Spectroscopy (STS)



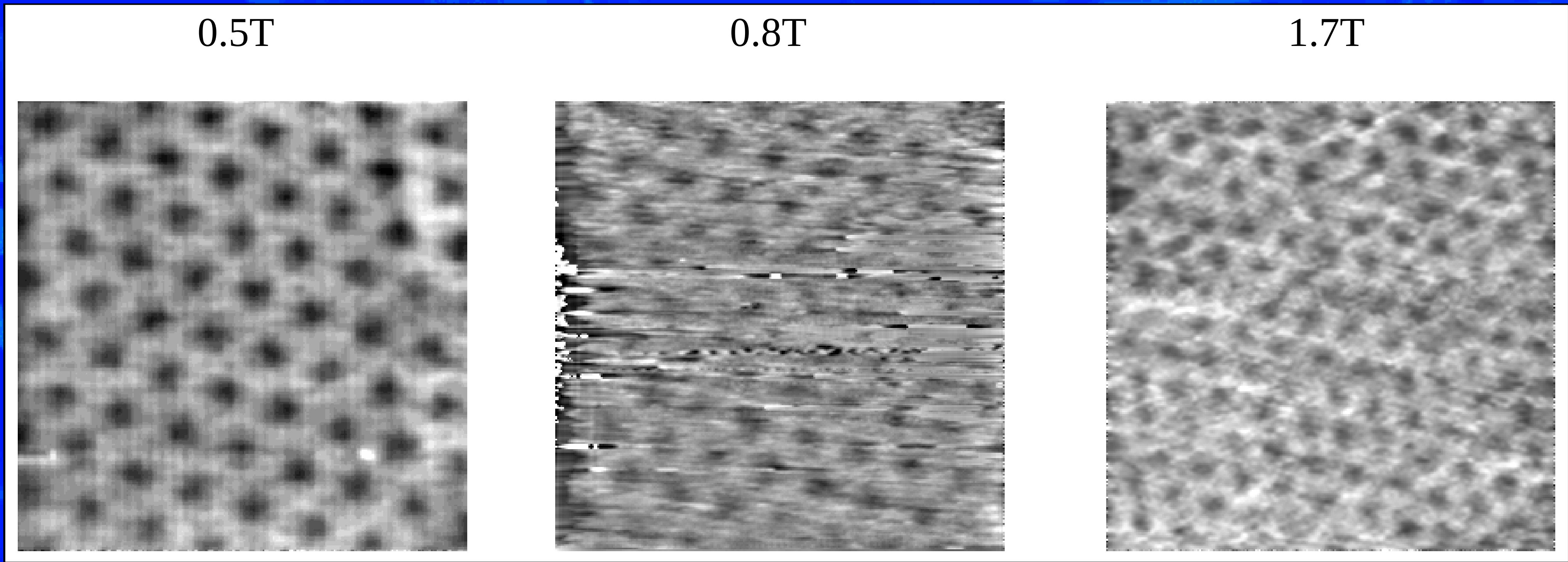




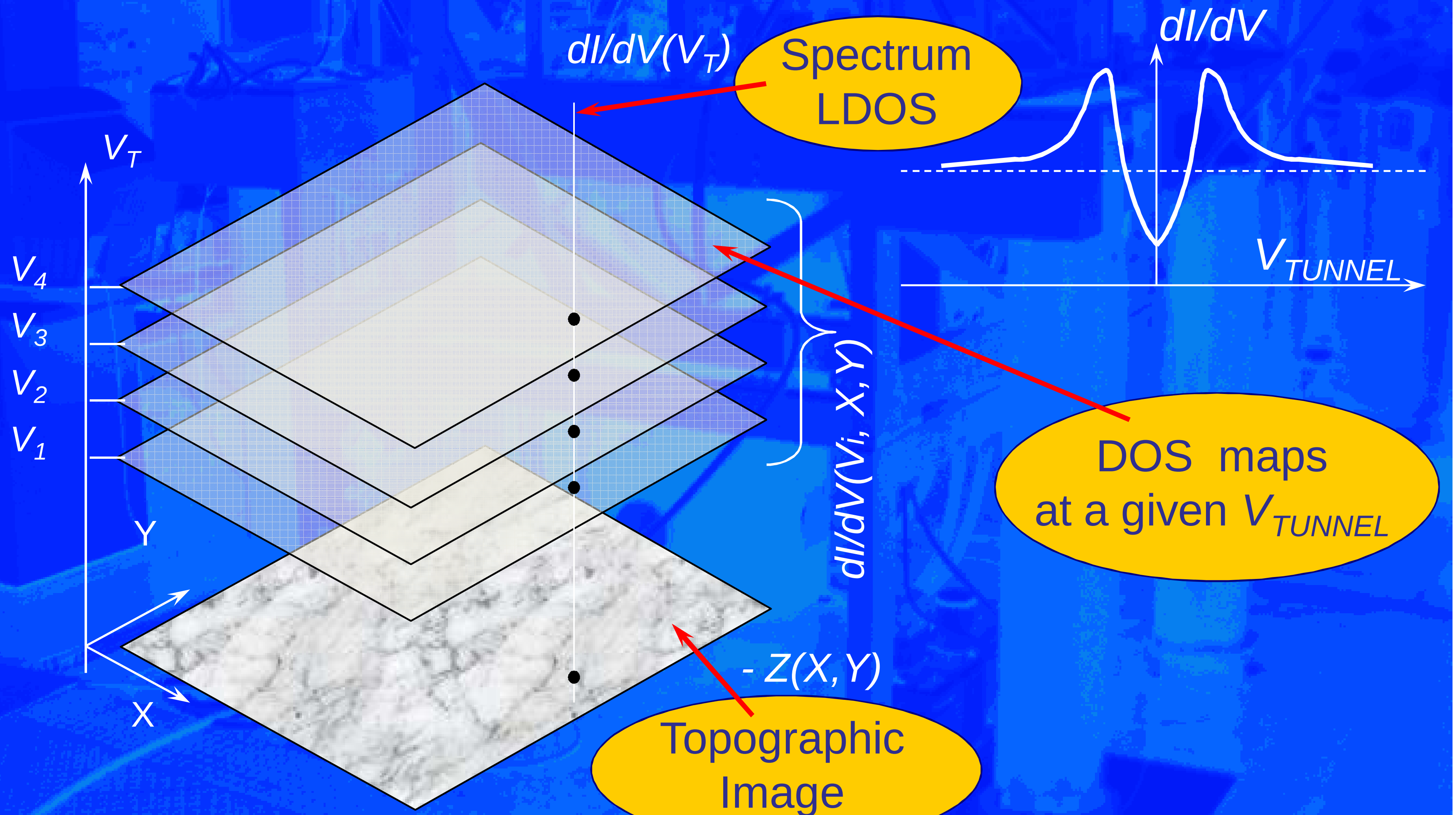
$$dI/dV(\mathbf{r}) \propto N(E,\mathbf{r})$$

Vortex Lattice Study (still picture)

Vortex lattice prepared in 2H-$NbSe_2$ at a given magnetic field:



STM/STS : Scanning Tunneling Spectroscopy



OUTLINE

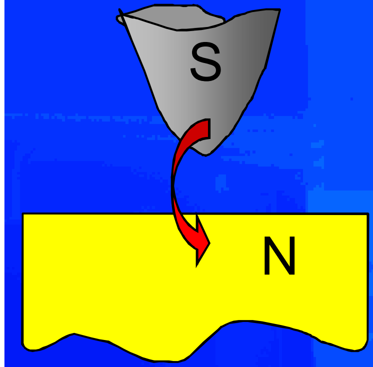
Scanning Tunneling Microscopy (STM) and Spectroscopy (STS)

1. Physical background

2. How to make it, how it looks like

3. Spectroscopy of Superconductors ⇨ MgB_2

4. Other strongly correlated materials



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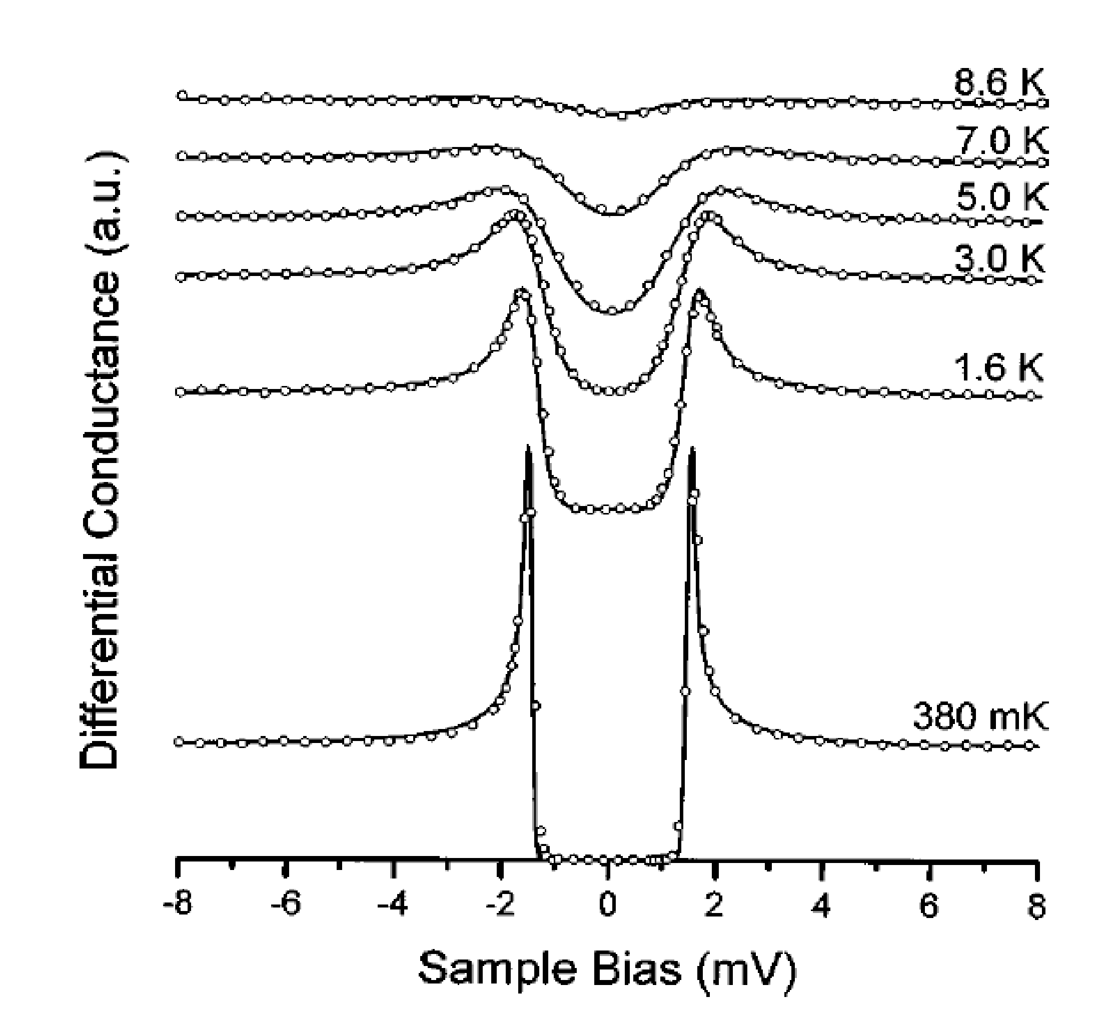
Gap 2Δ in the excitation spectrum:

$$N_s(E) = N(0)\frac{E}{\sqrt{(E^2-\Delta^2)}}$$

BCS

$$\frac{2\,\Delta(0)}{k\,T_c} \approx 3.5$$

MgB_2: Tc=39K → $\Delta(0)$=6mV



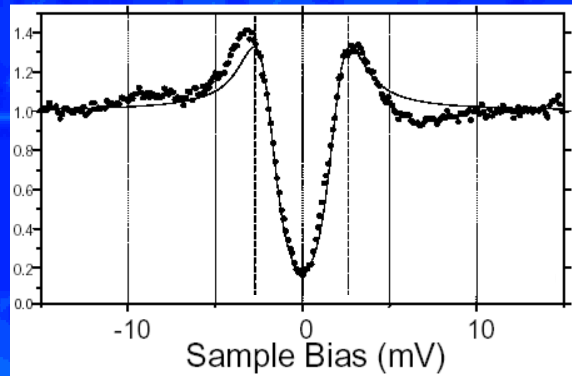
Pan, Davis, Univ. de Berkeley.(APL,1998)

STS on Granular MgB_2

Result on more than 10^6 tunneling spectra locally measured:

- On ~99% of spectra : Single Gap DOS:

  Small Gap Energy : Δ = 2.5±0.8 meV
  Strong « Pair-Breaking » : Γ = 0.3-0.5 meV

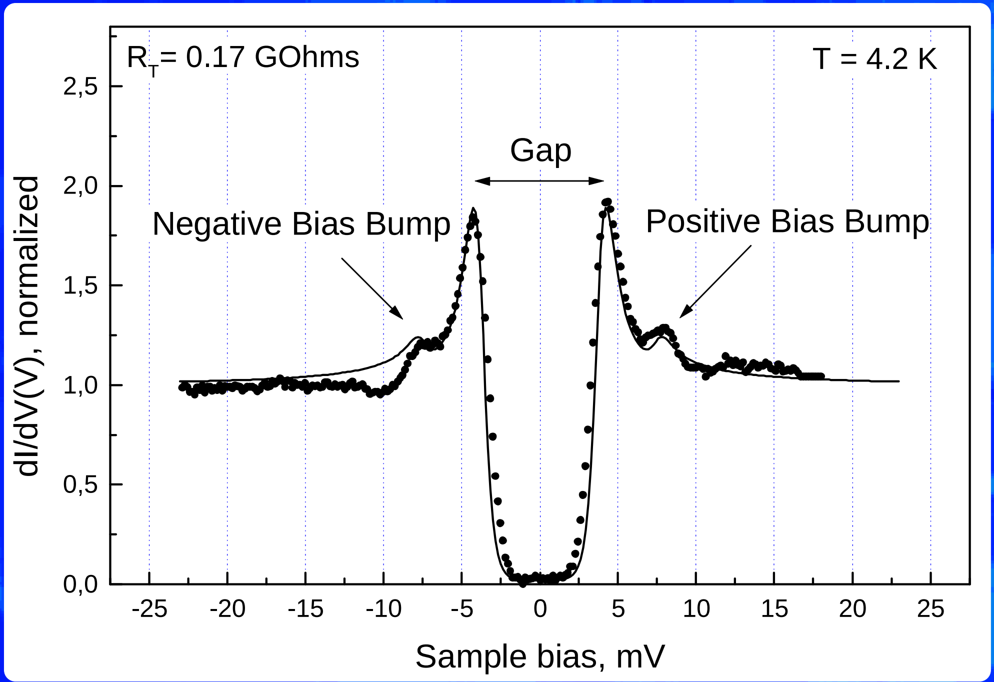


- On ~1% of spectra (hundreds spectra): Some « strange » DOS!

???

STS on Granular MgB_2

- **Fit** : weighted sum of two BCS DOS



$$\rho_S^L = \Re e\left[\frac{\varepsilon - i\Gamma}{\sqrt{(\varepsilon - i\Gamma)^2 - \Delta_L^2}}\right]$$

$$\rho_S^S = \Re e\left[\frac{\varepsilon - i\Gamma}{\sqrt{(\varepsilon - i\Gamma)^2 - \Delta_S^2}}\right]$$

$$\rho_N(\varepsilon) = Const$$

$$\sigma^{L,S} \propto \int_{-\infty}^{+\infty} g(\varepsilon, V)\, \rho_S^{L,S}(\varepsilon - eV)\, d\varepsilon$$

$$\sigma \propto C \times \sigma^L + (1 - C) \times \sigma^S$$

C = 0.13 ⇒ Δ_L = 7.4 mV

1-C = 0.87 ⇒ Δ_S = 3.5 mV

Γ = 0.15 mV

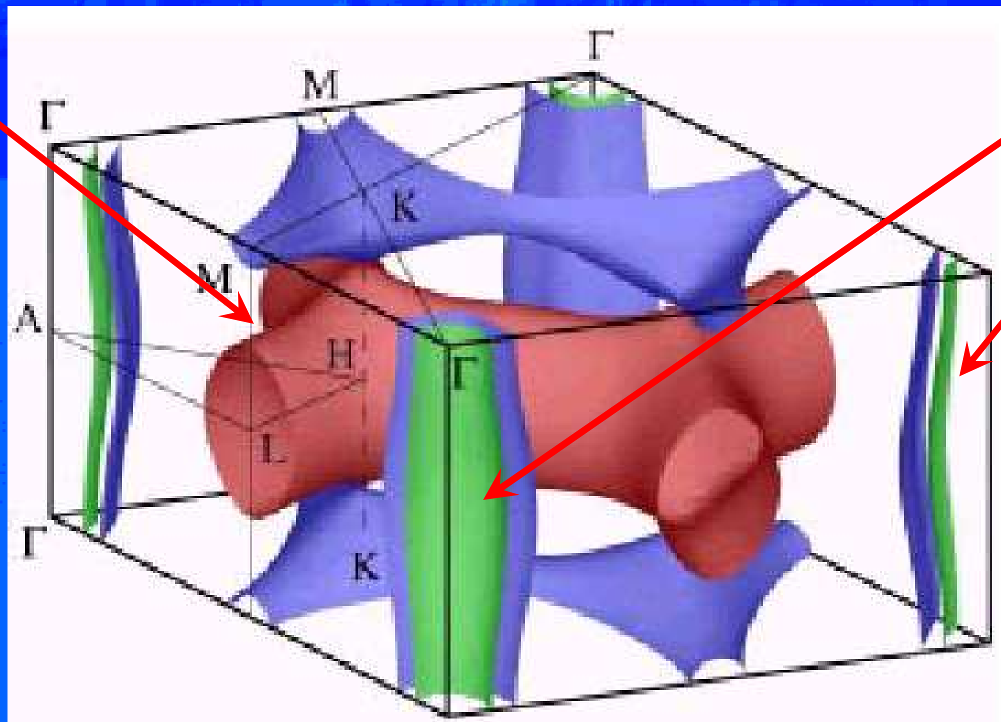
STS on Granular MgB_2 : Questions

- « Strange » spectra are rare– are they relevant?
- Why such a statistic (1%)?
- What is the physical background of the effect?

MgB_2 : Electronic Structure

3D

Quasi-2D



Weak EPC

Strong EPC

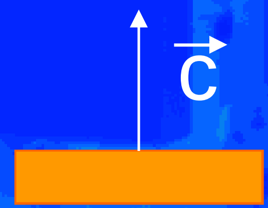
E_{2G} Phonons

J. Kortus et al. Cond-mat./0101446, PRL (2001)

STS on Granular MgB_2

- MgB_2 is anisotropic material

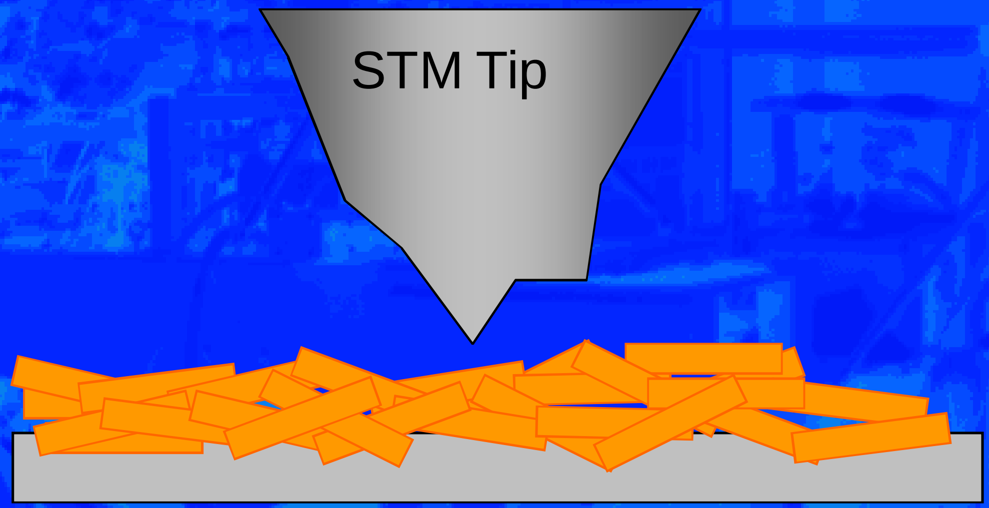
⇓ The form of pellets:



- Complex Fermi surface : 2D (ab-plane) and 3D

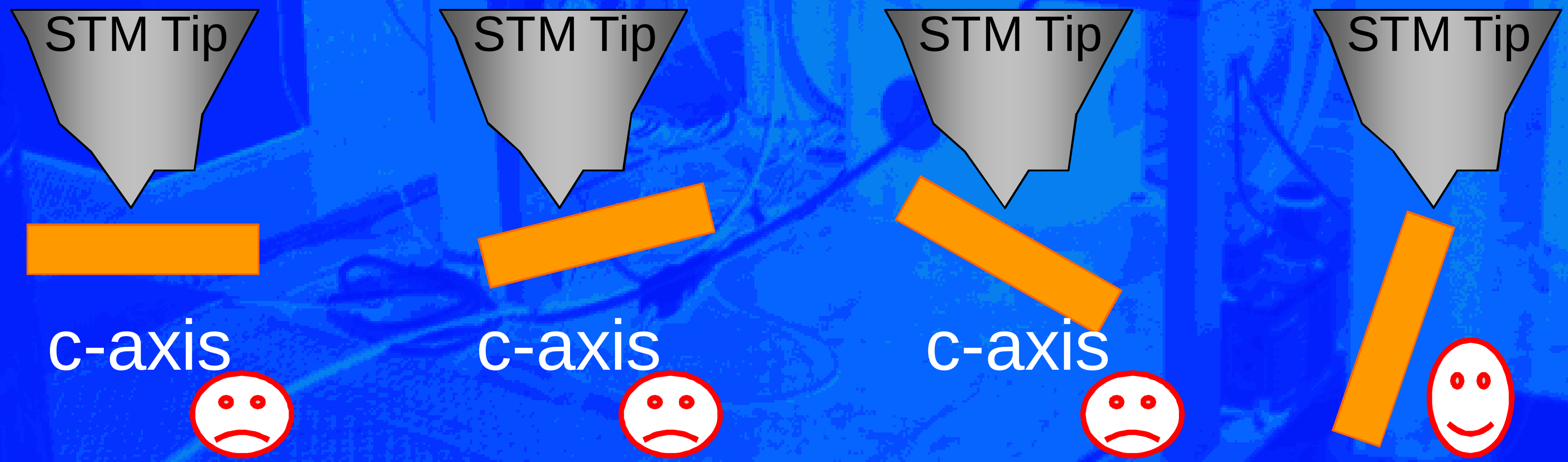
⇓ Orientation-dependent Tunneling!

STS on Granular MgB_2



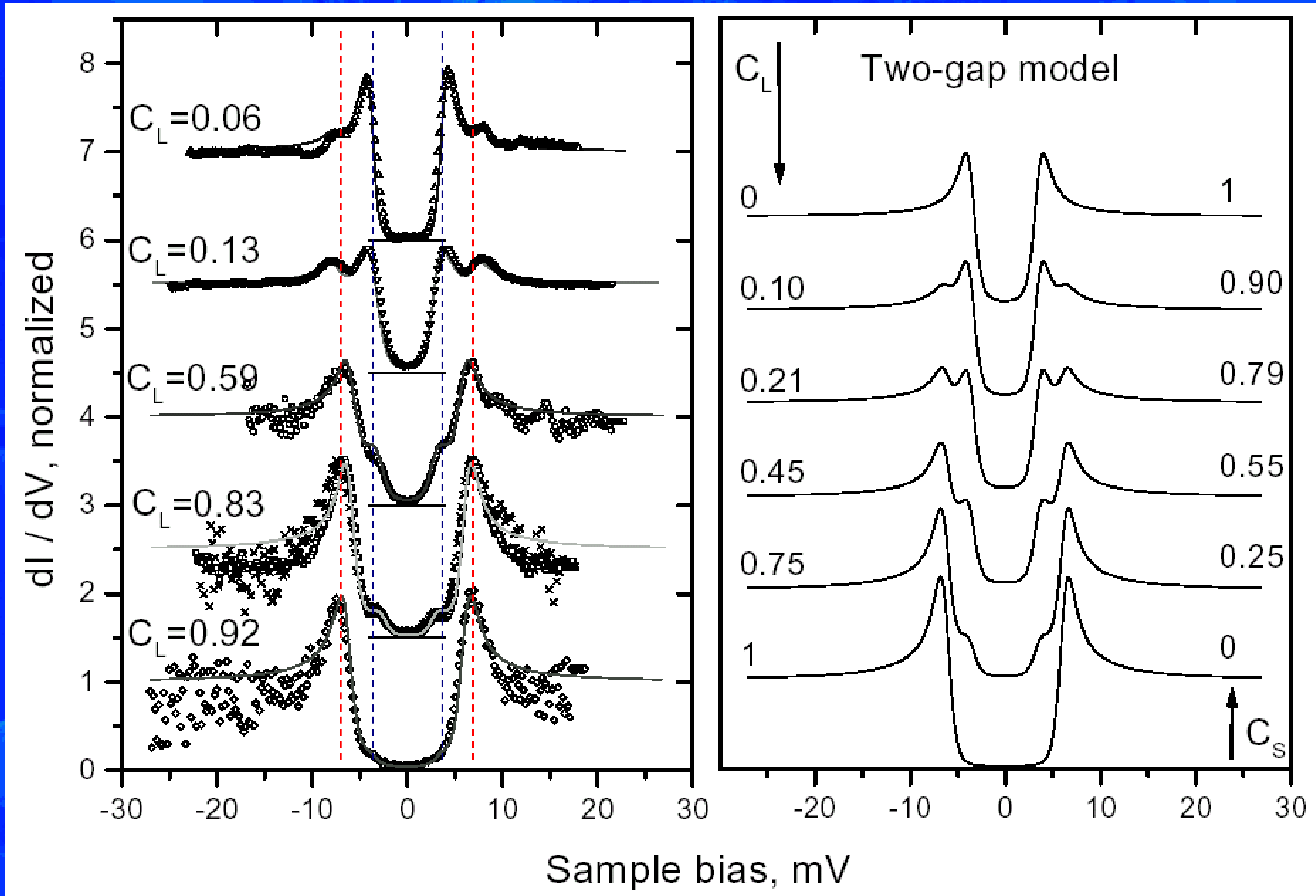
➡ STM/STS on pellets:

➡ Local Geometry favours the tunneling into the 3D-band

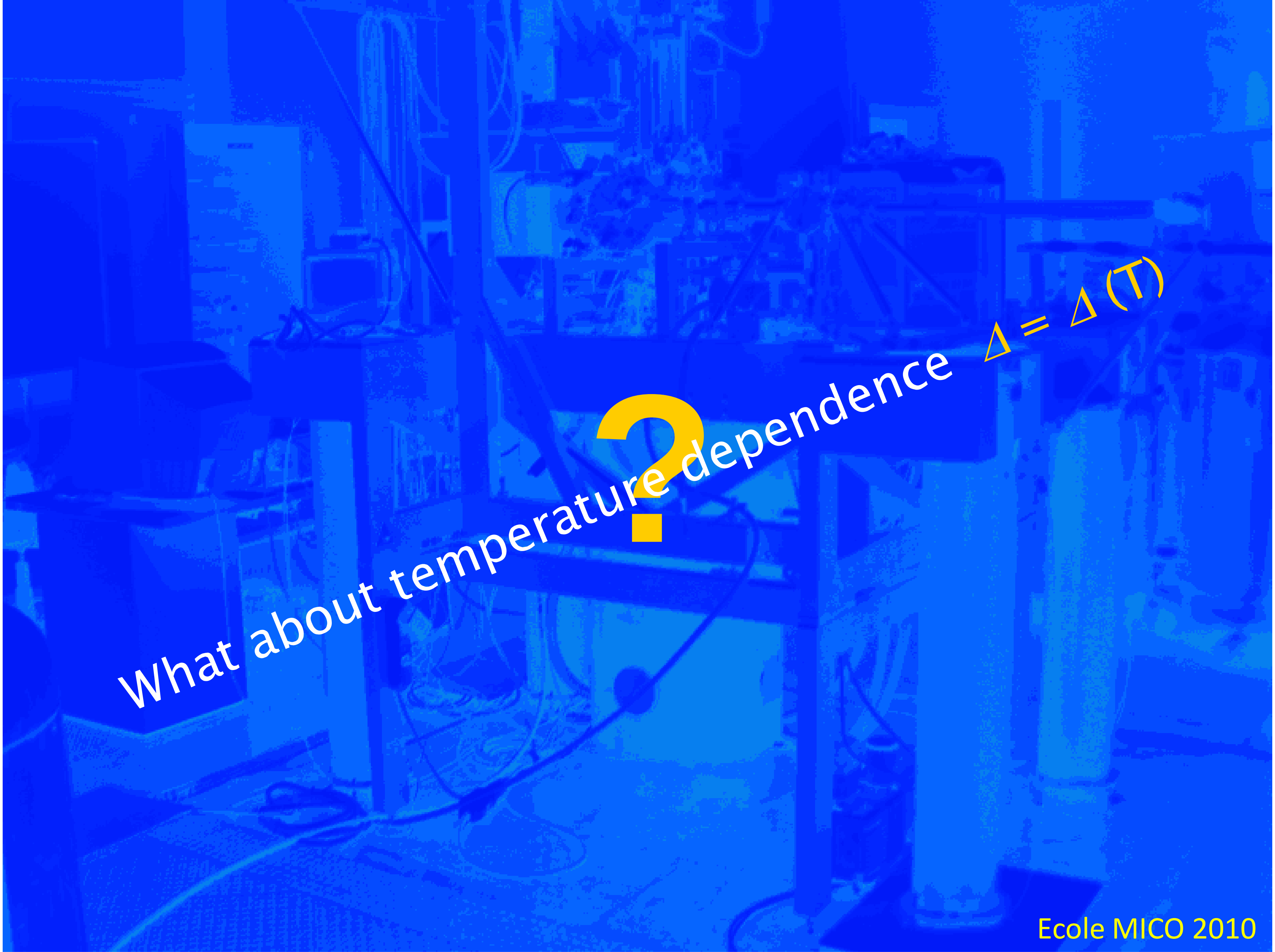


STS on Granular MgB_2

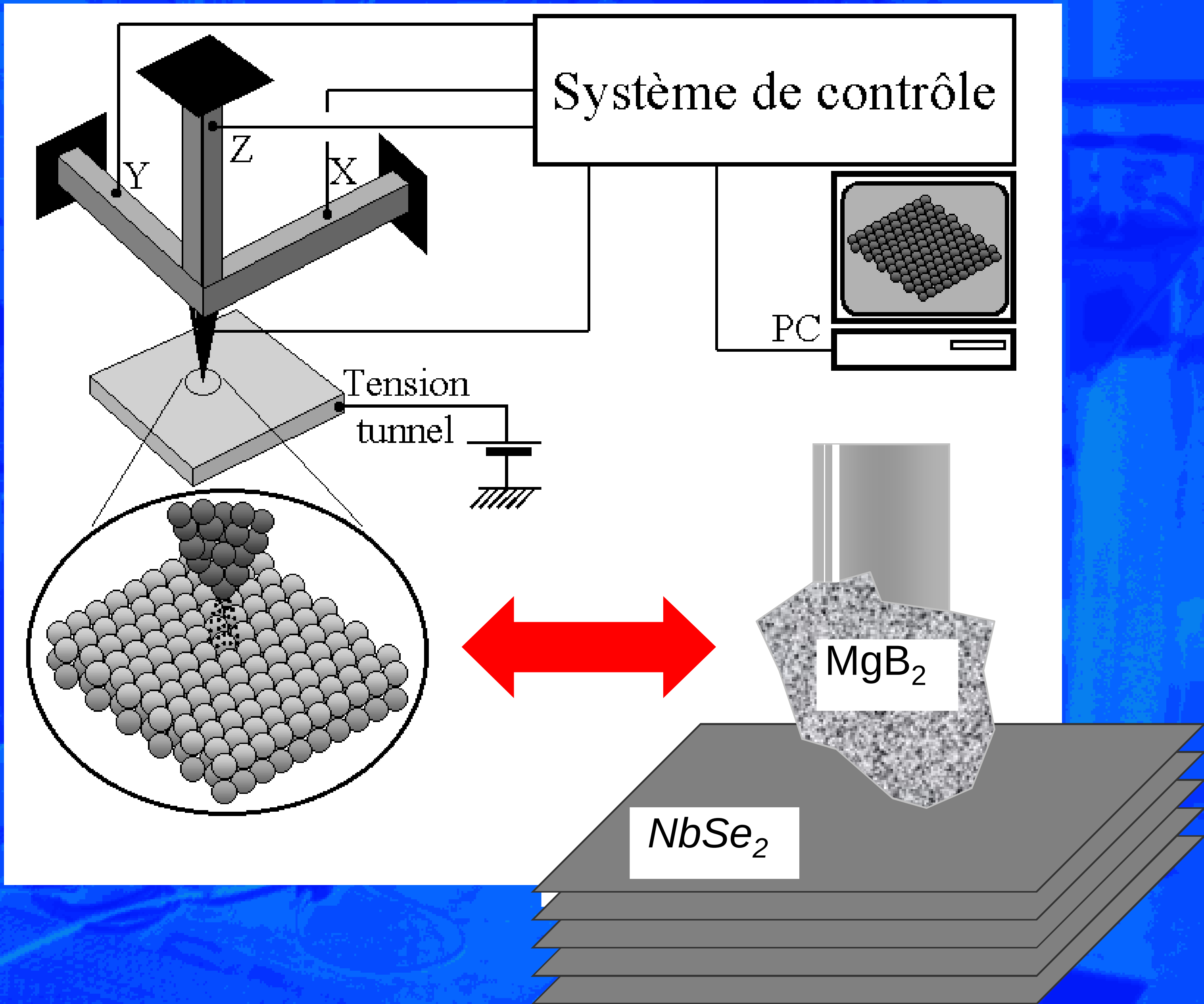
- Selected : SIN spectra with different 2D/3D tunneling weights



F. Giubileo et al. Cond-mat/0105146, Europhys. Lett. (2002)

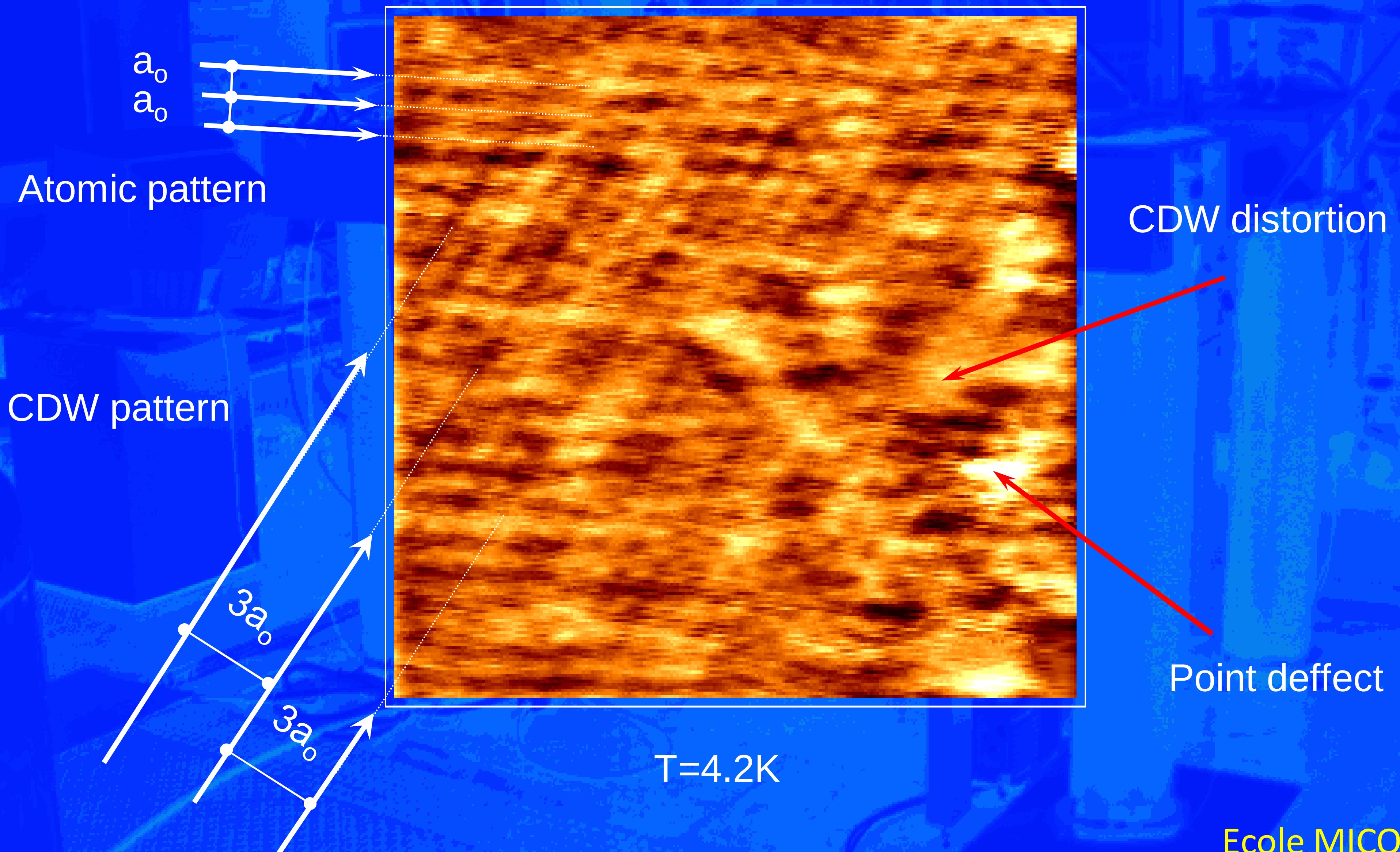

What about temperature dependence $\Delta = \Delta(T)$
?

Inverted Junction Experiment

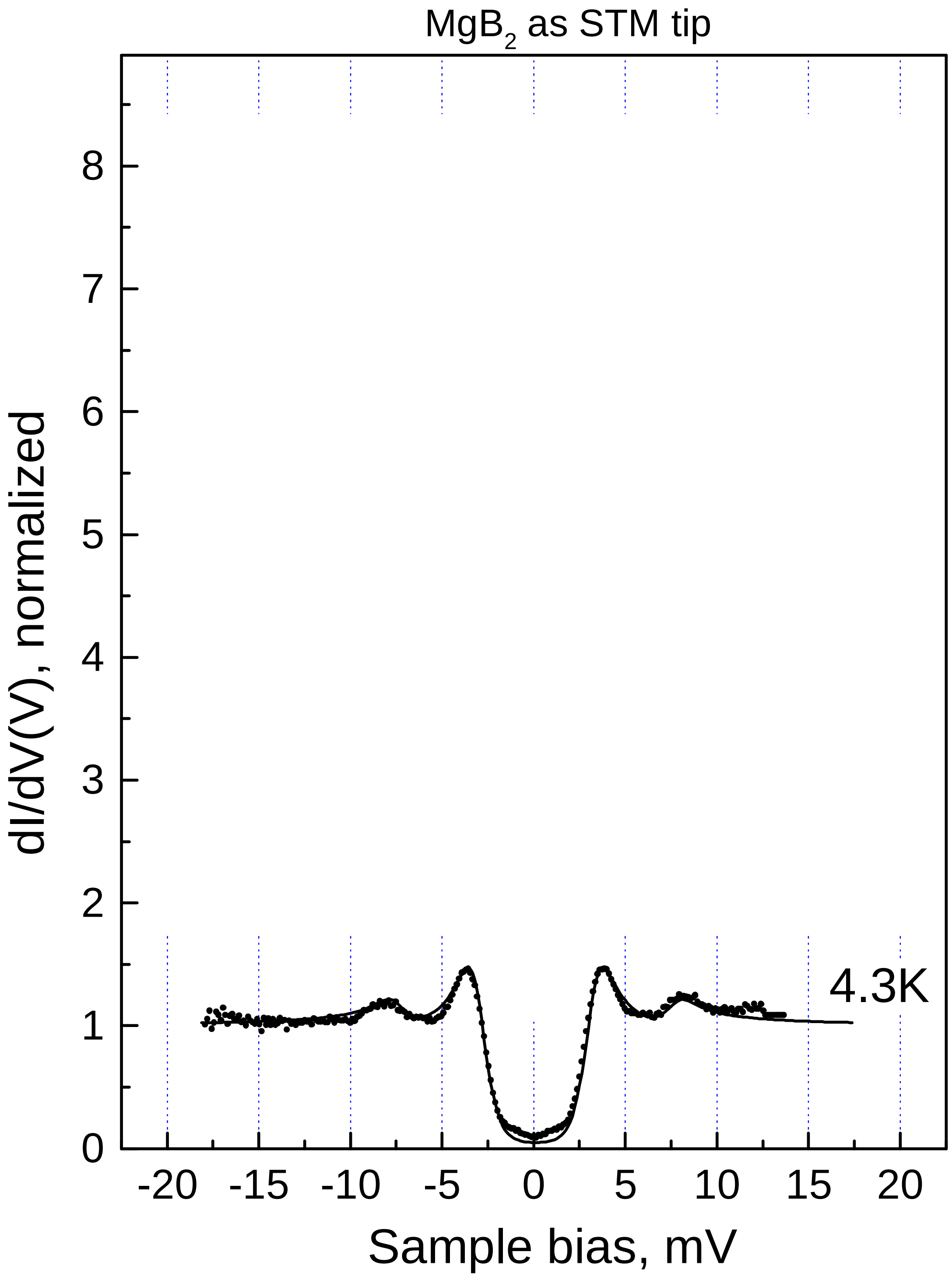


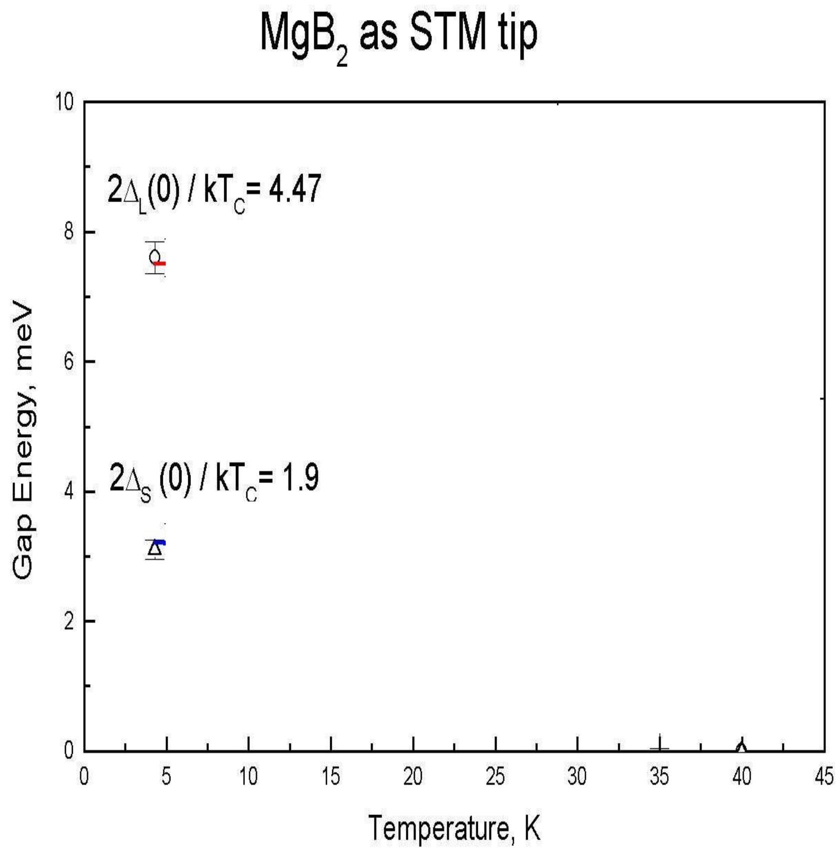
Inverted Junction Experiment

MgB_2 tip – sample of 2H-$NbSe_2$



T=4.2K

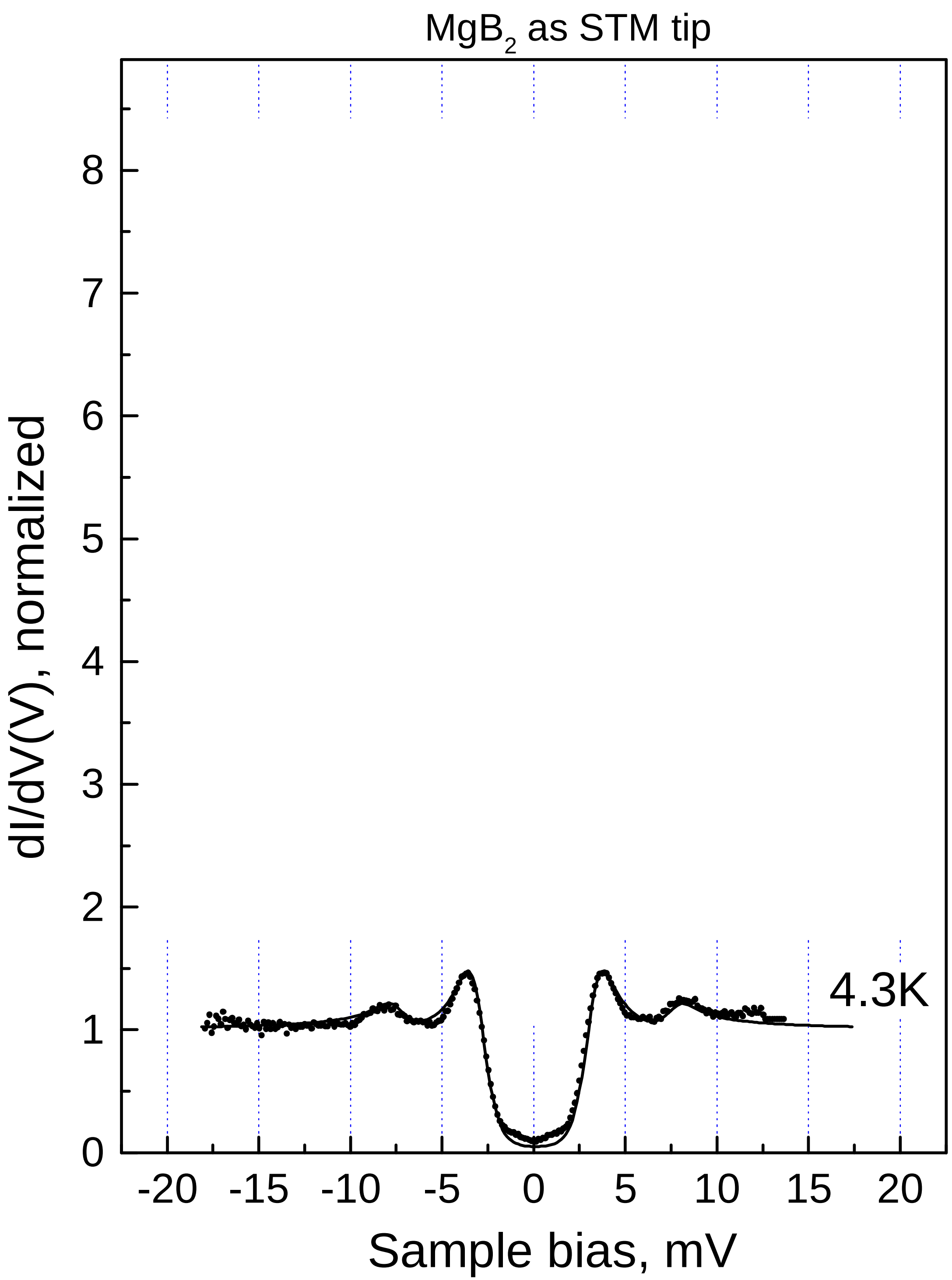


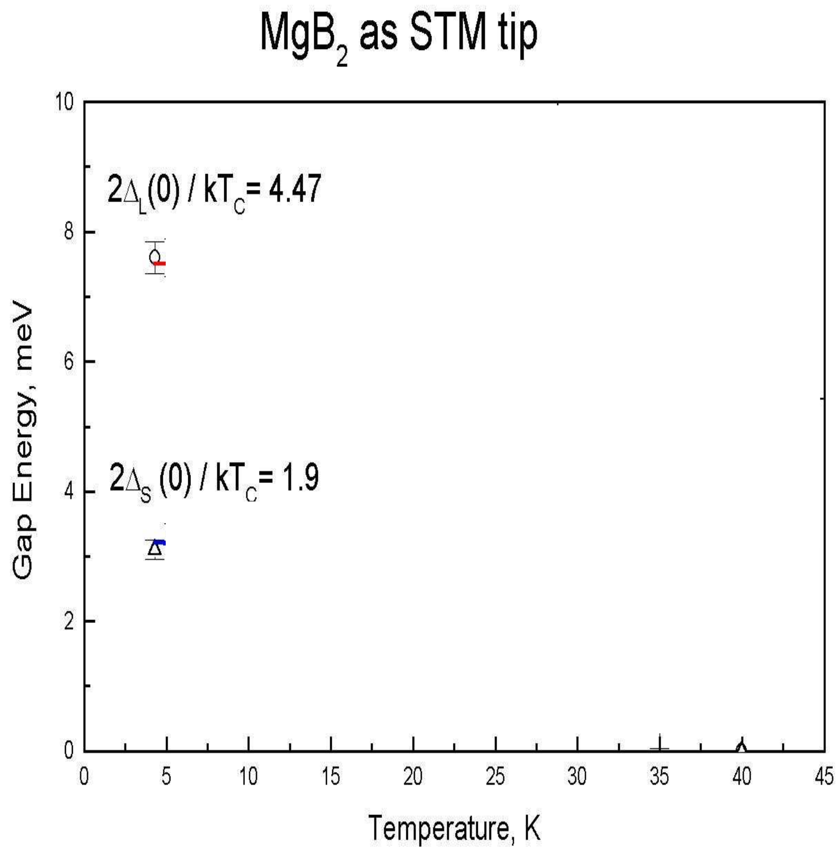


$$\sigma \propto C \times \sigma^{L} + (1-C) \times \sigma^{S}$$

Free Parameters :

Δ_L, Δ_S, C, Γ





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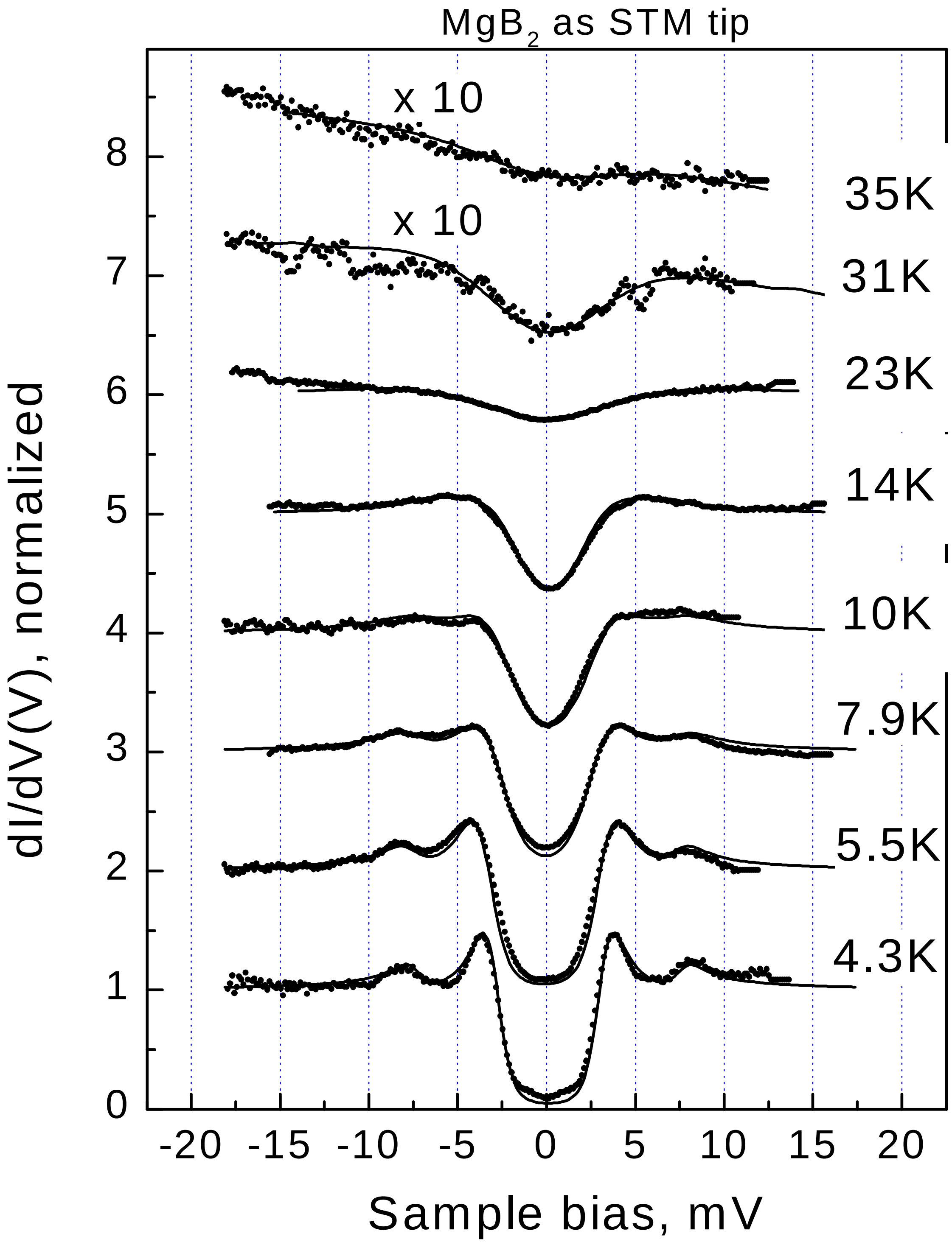
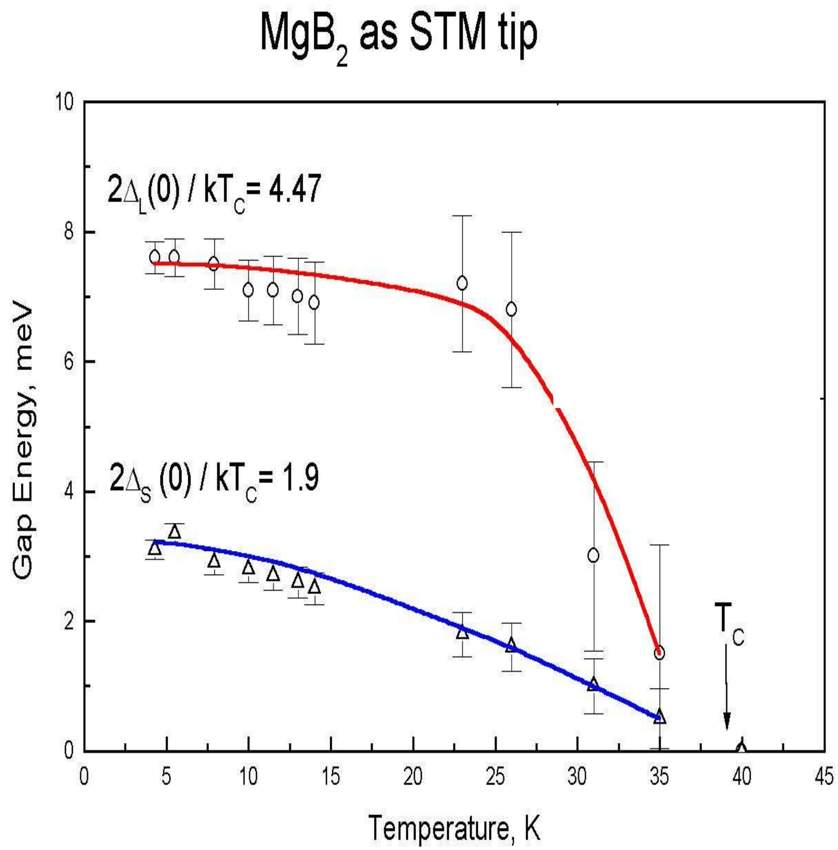
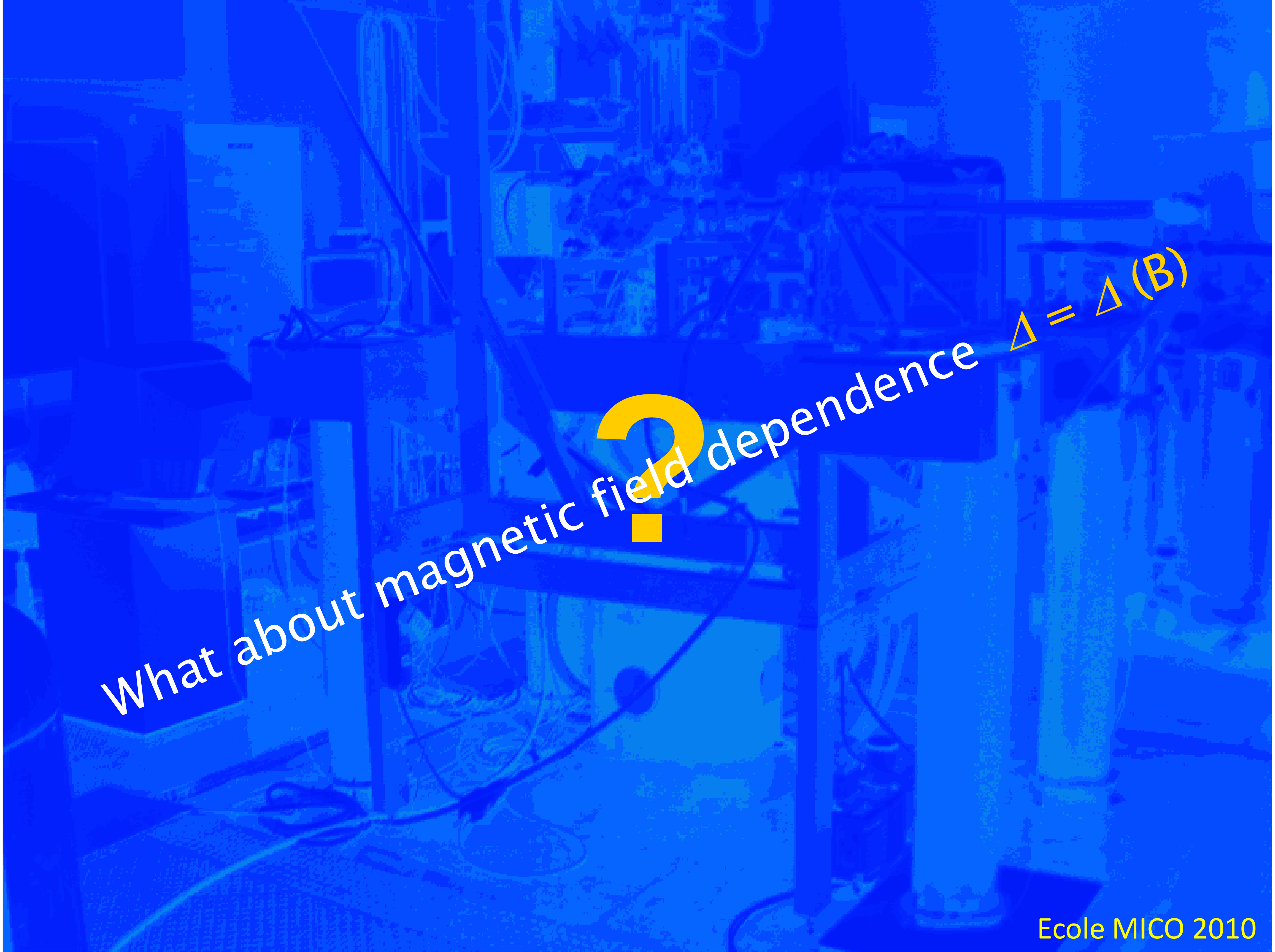
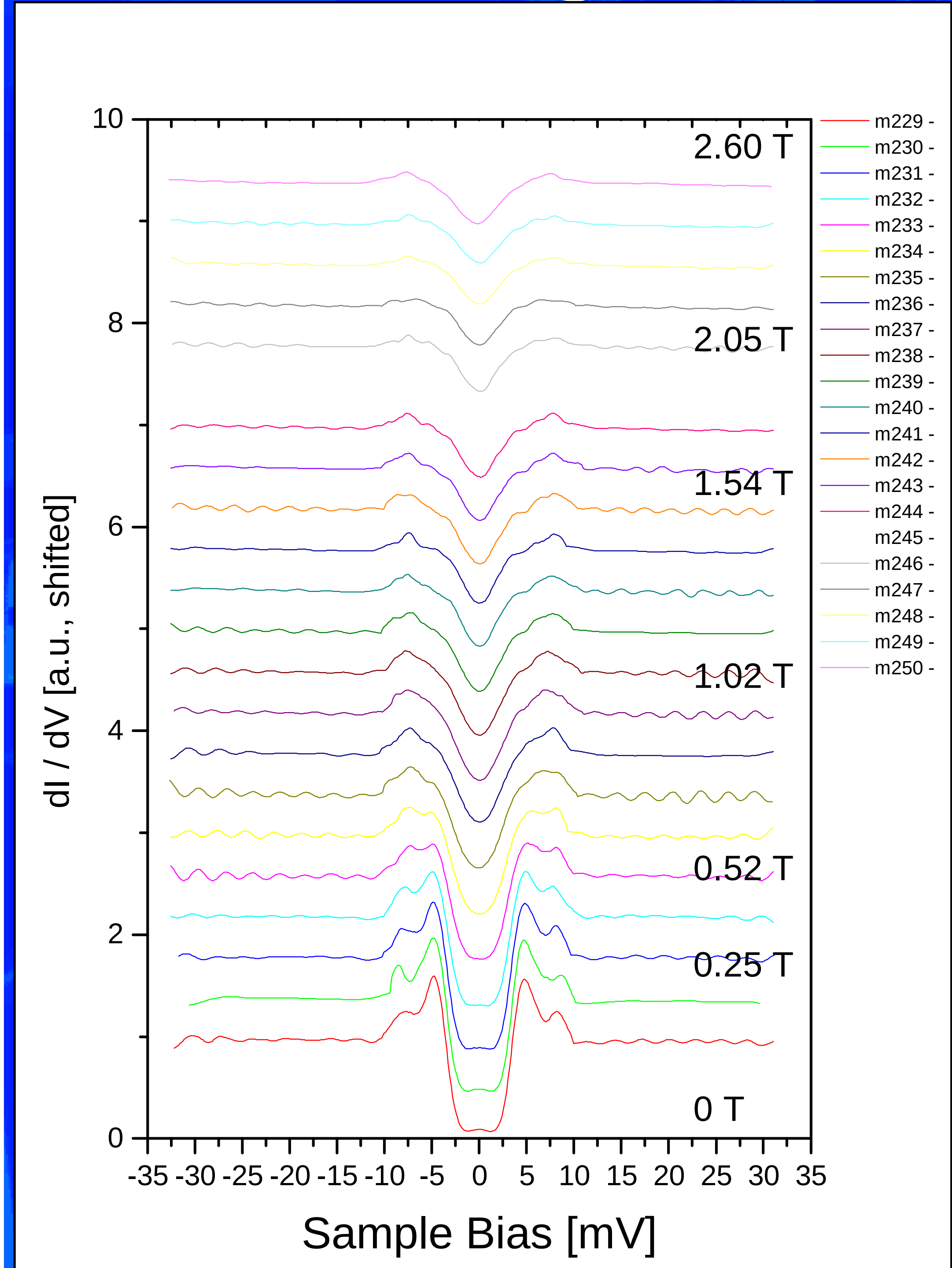




F. Giubileo et al.
cond-mat/0105592, Phys. Rev. Lett. 87 (2001)


What about magnetic field dependence $\Delta = \Delta(B)$
?

Magnetic Field Dependence



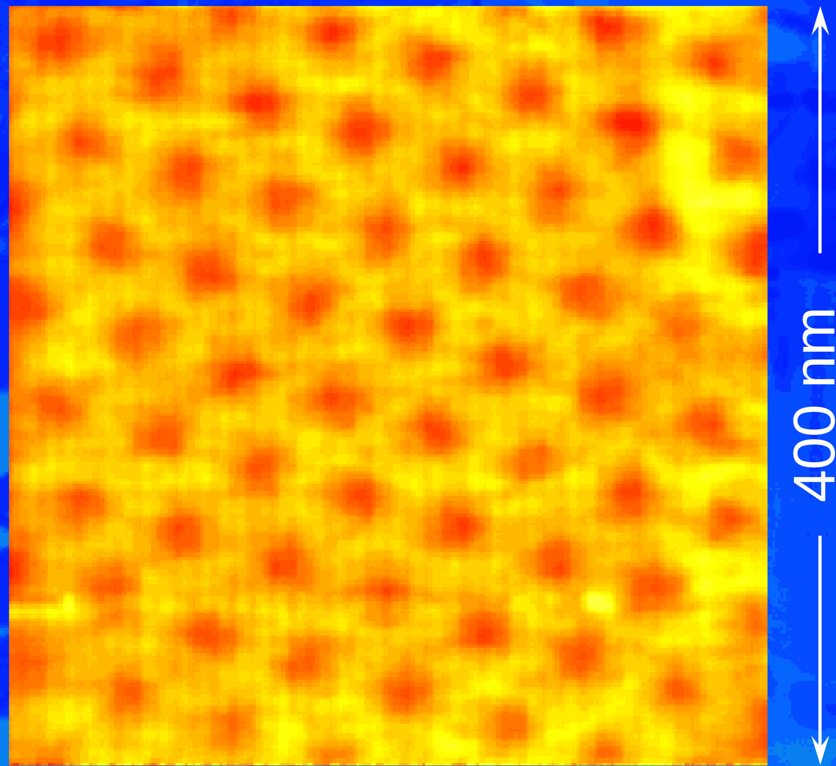
- Δ_S , Δ_S *versus* (B)

- Experiment:
  -both « gaps » are present at 2T!
  - large gap resists much better

« Lazy Fisherman » Method of Vortex Study

Fishing Vortices

Scanning Spectroscopy

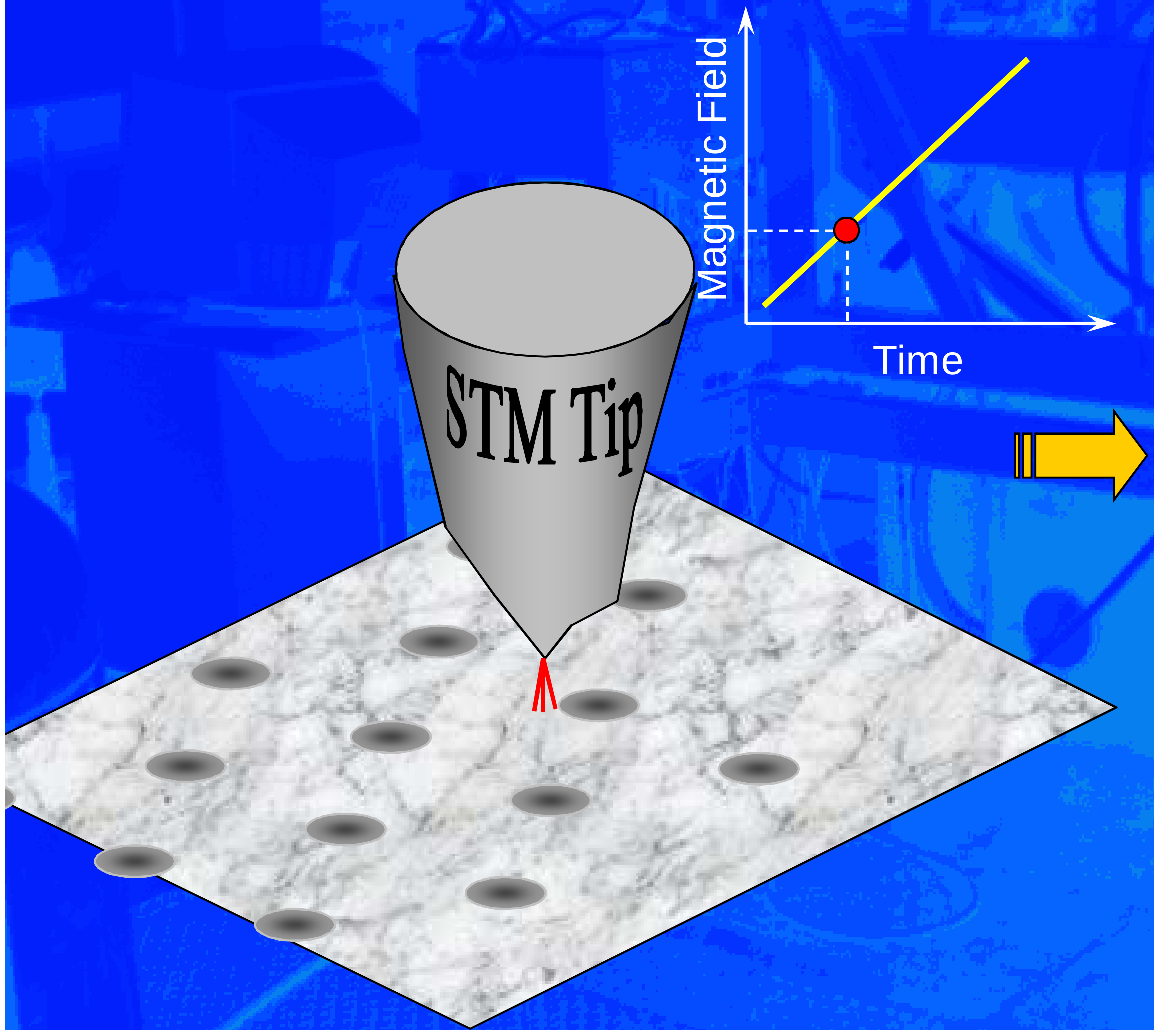


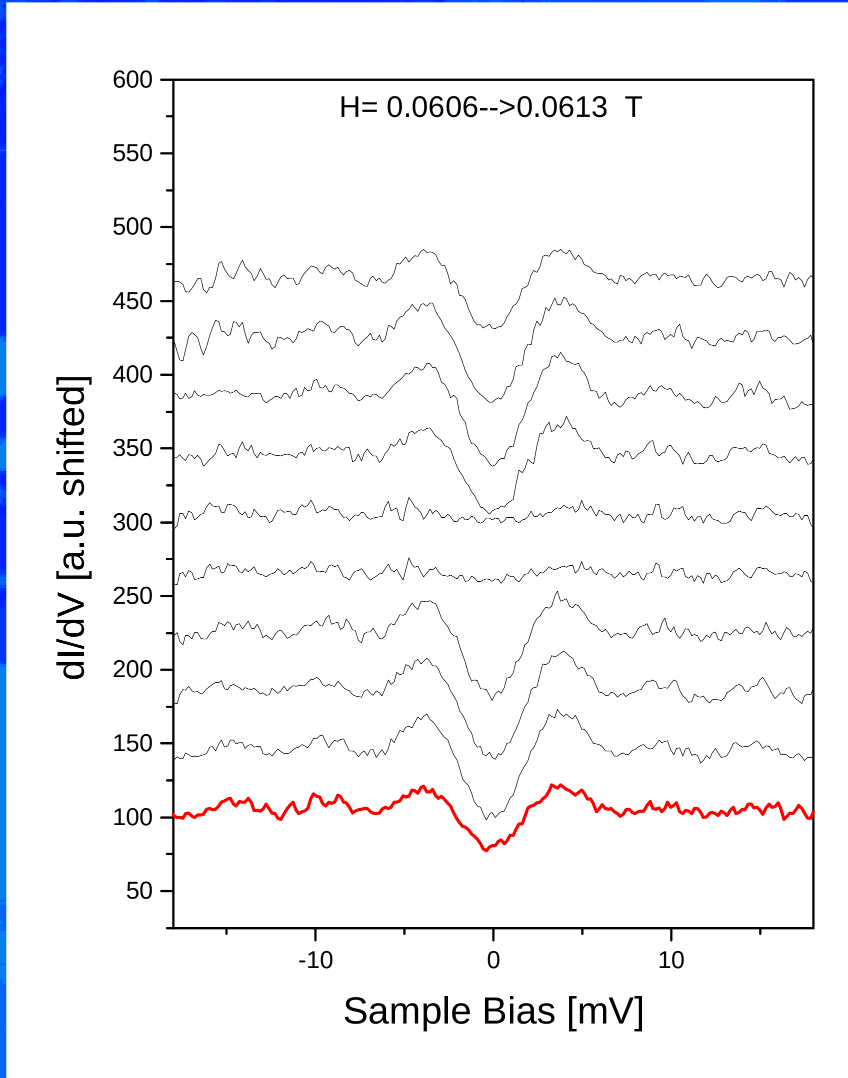
T = 4.2 K	
B = 1.0 T	

Fishing Vortices

Lazy Fisherman :
« Novel » Method of Vortex Studying

Local Spectroscopy





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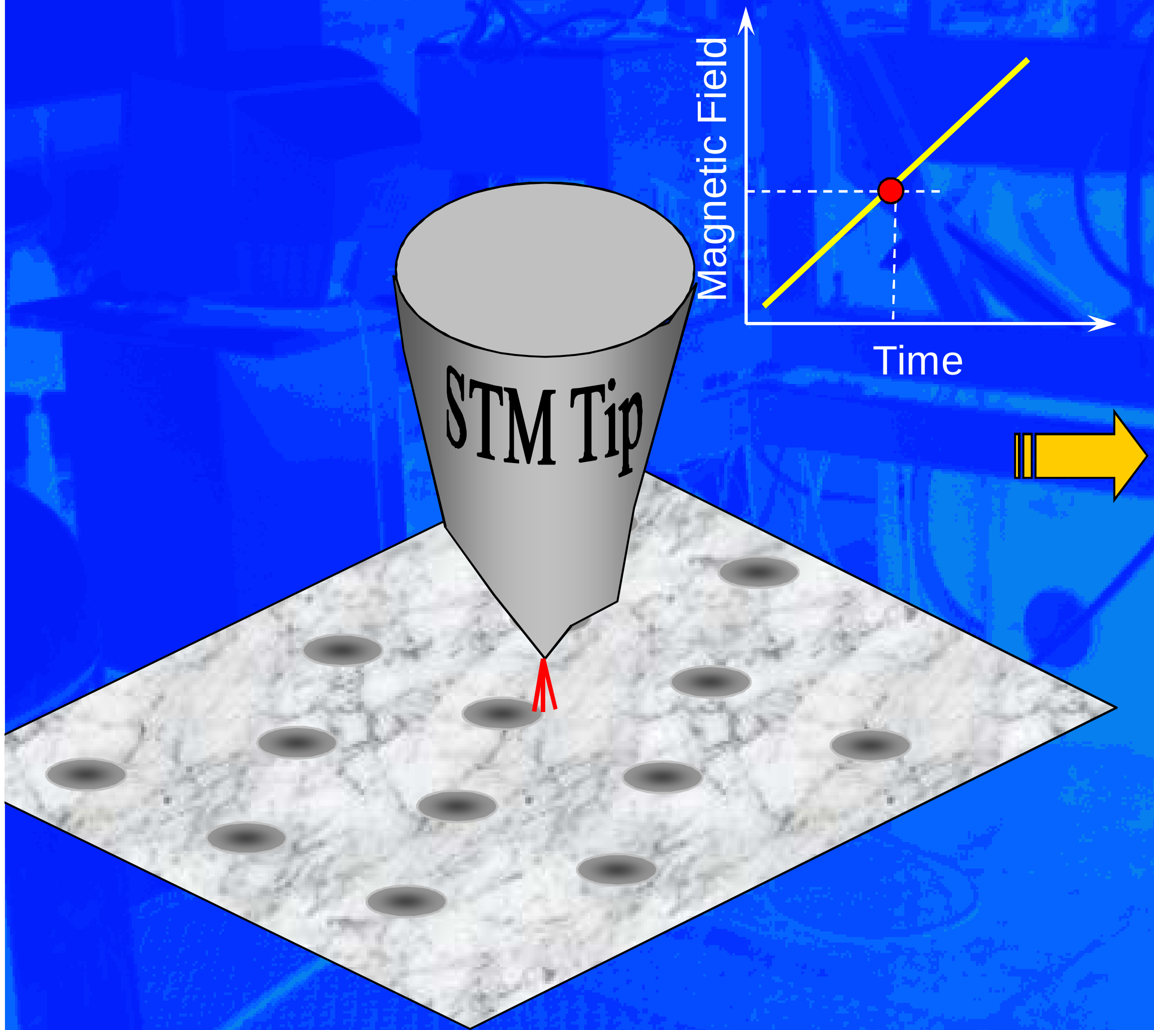

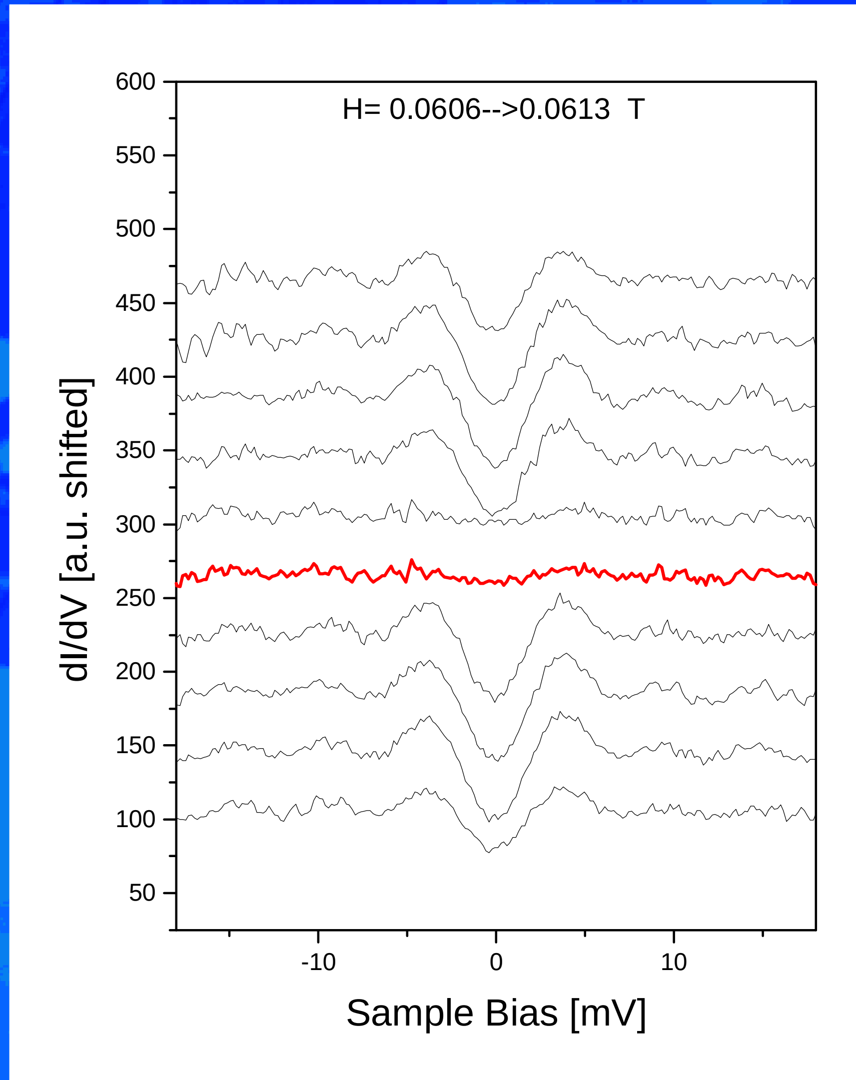

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« Novel » Method of Vortex Studying

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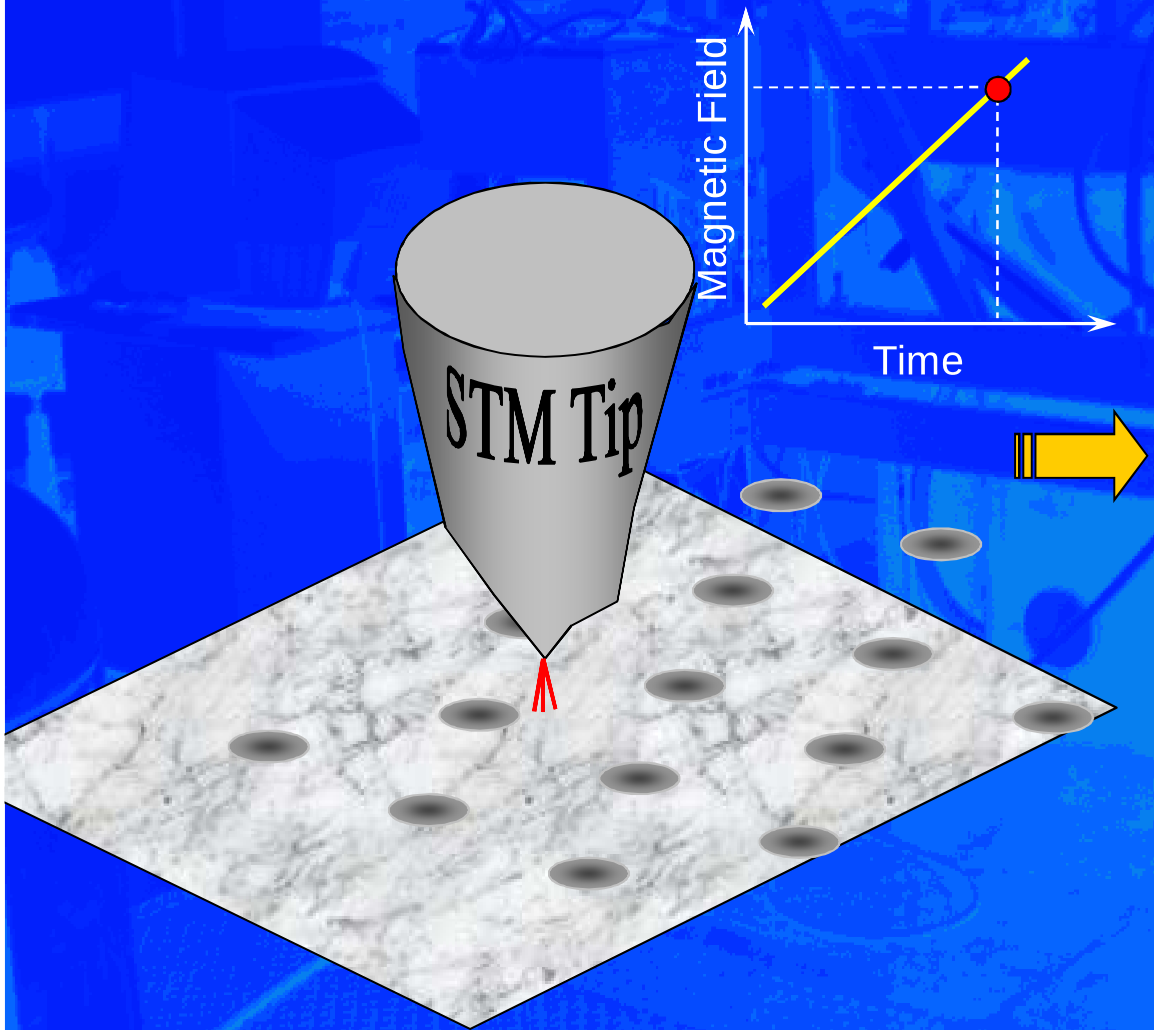
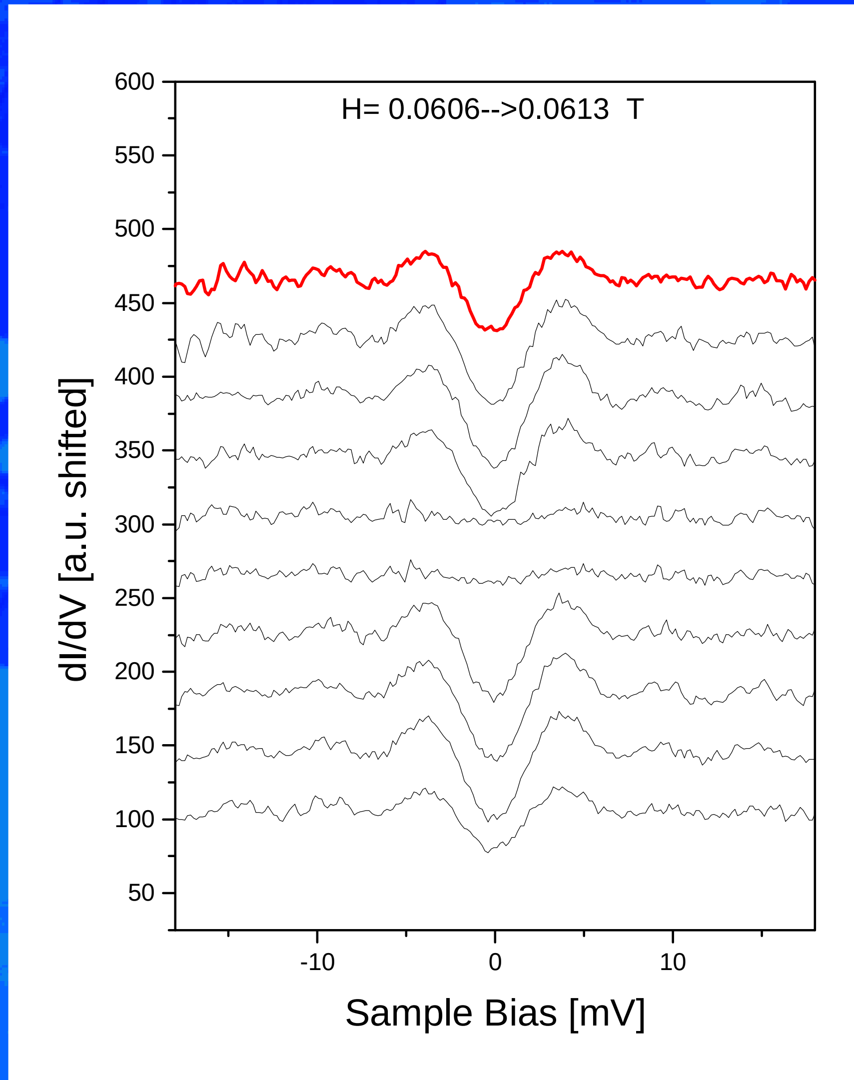
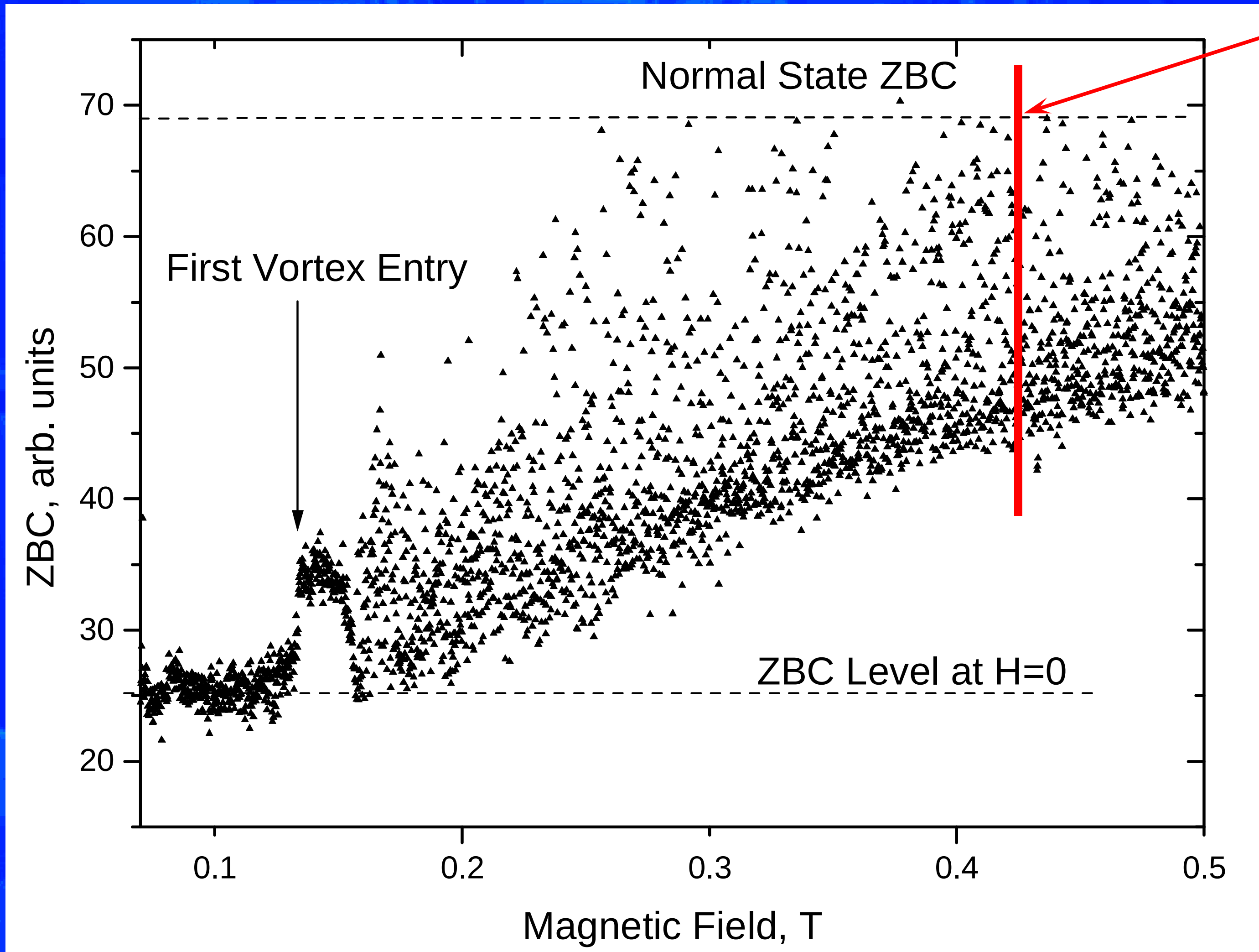




Lazy Fisherman :
« Novel » Method of Vortex Studying

- Application to MgB_2

Profile Analysis : Size of the Vortex Cores



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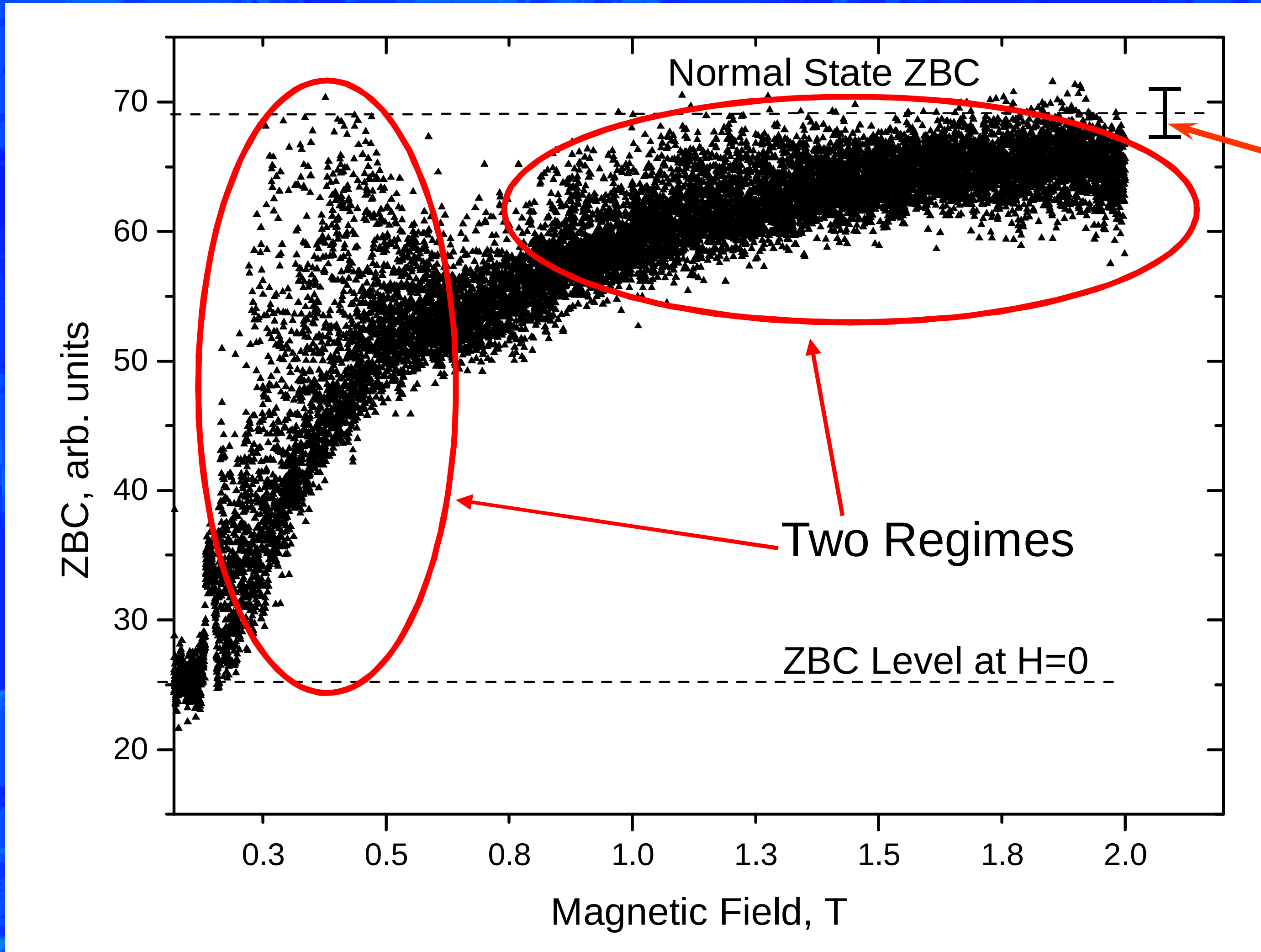


OUTLINE

Scanning Tunneling Microscopy (STM) and Spectroscopy (STS)

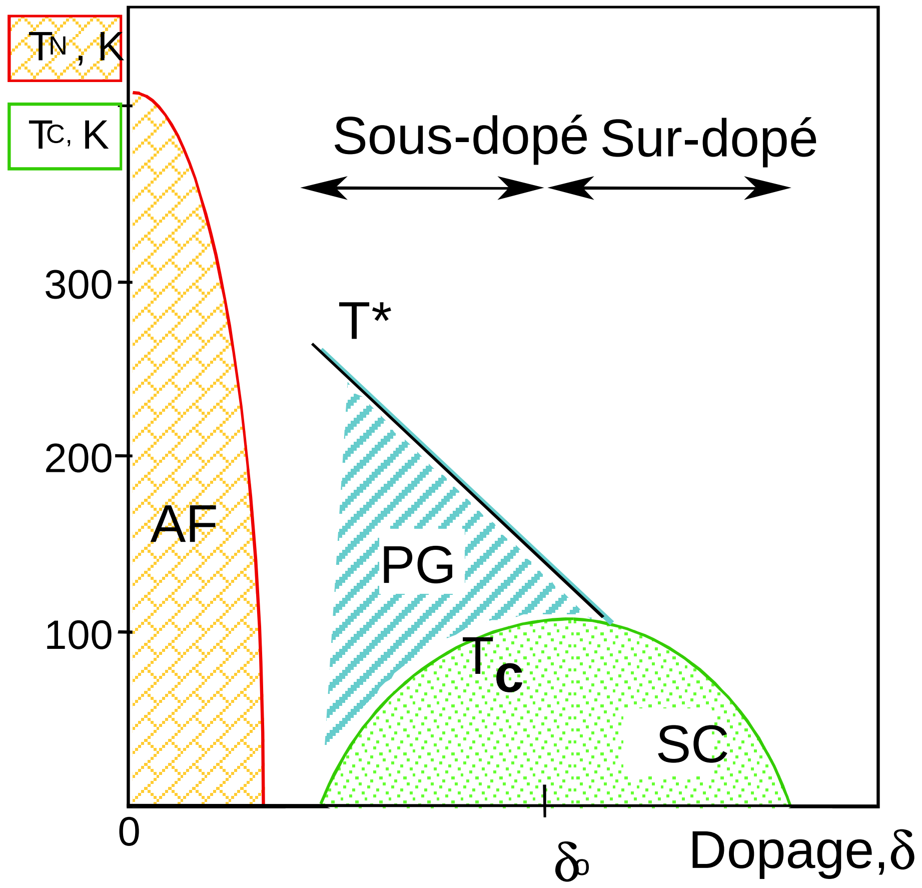
1. Physical background

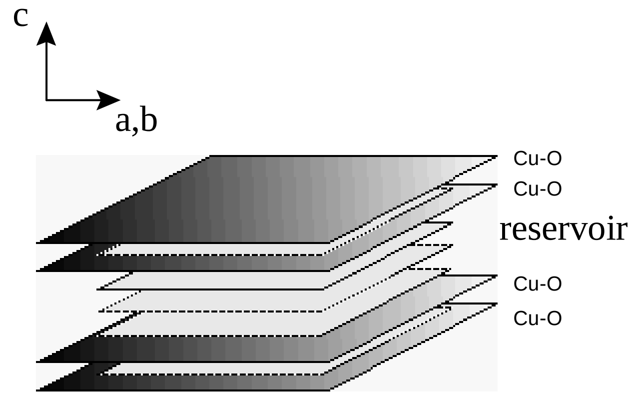
2. How to make it, how it looks like

3. Spectroscopy of Superconductors ⇨ HTSC

4. Other strongly correlated materials

Supraconductivité à haute Tc

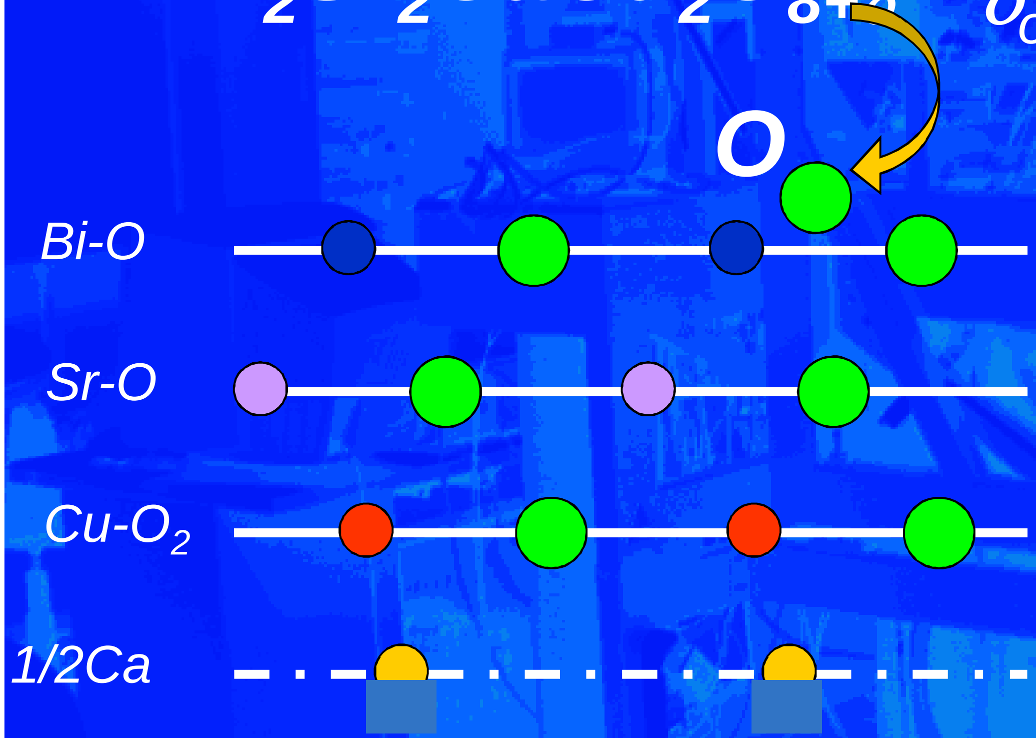


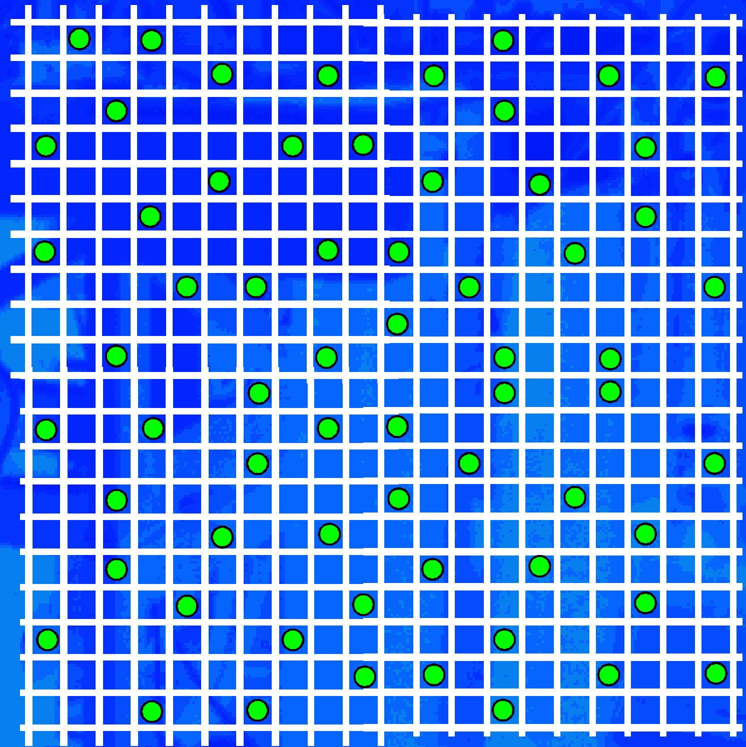


	BiSrCaCuO	$2H$-NbSe$_2$
T_c	90 K	7,2 K
$\xi_\parallel$	20 Å	77 Å
$\xi_\perp$	2-5 Å	-
λ	2500 Å	700 Å
H_{c2}	110 T	15 T
n	$\sim 10^{-2}$ Å^{-2}	~ 2 Å^{-2}

Supraconductivité à haute Tc

$Bi_2Sr_2CaCu_2O_{8+\delta}$ $\delta_{opt} \approx 0,16$



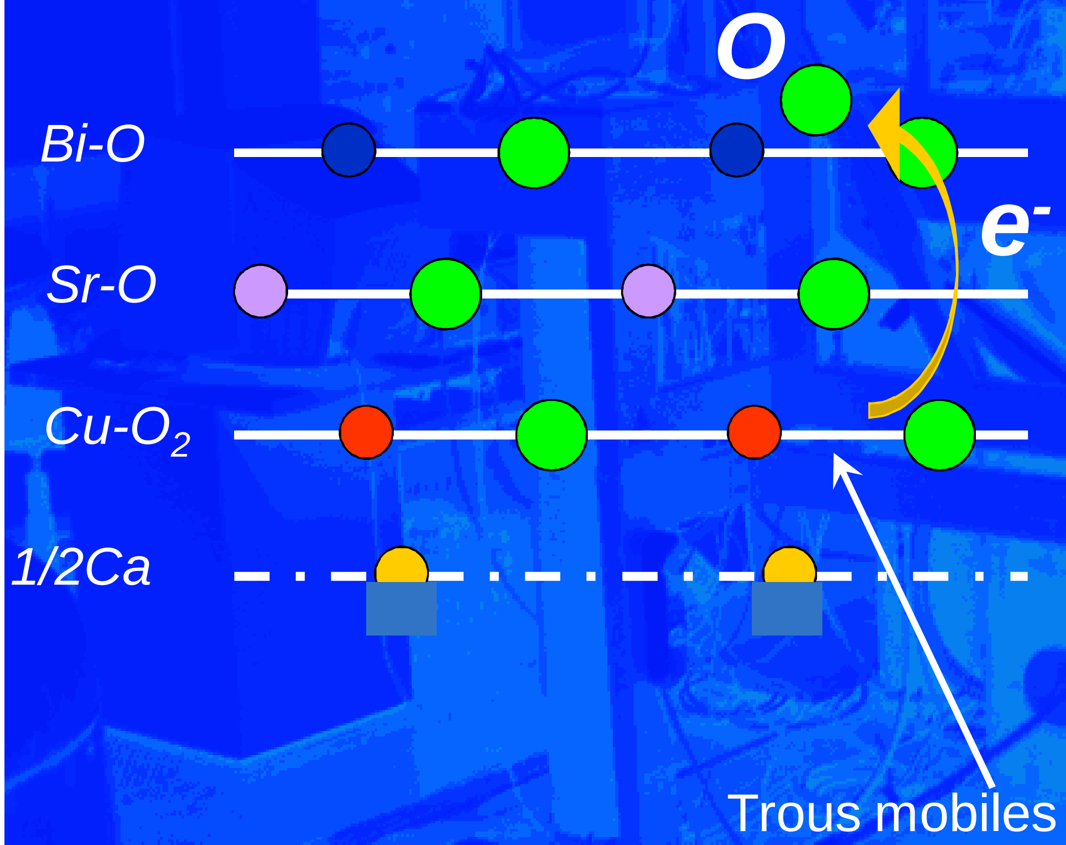


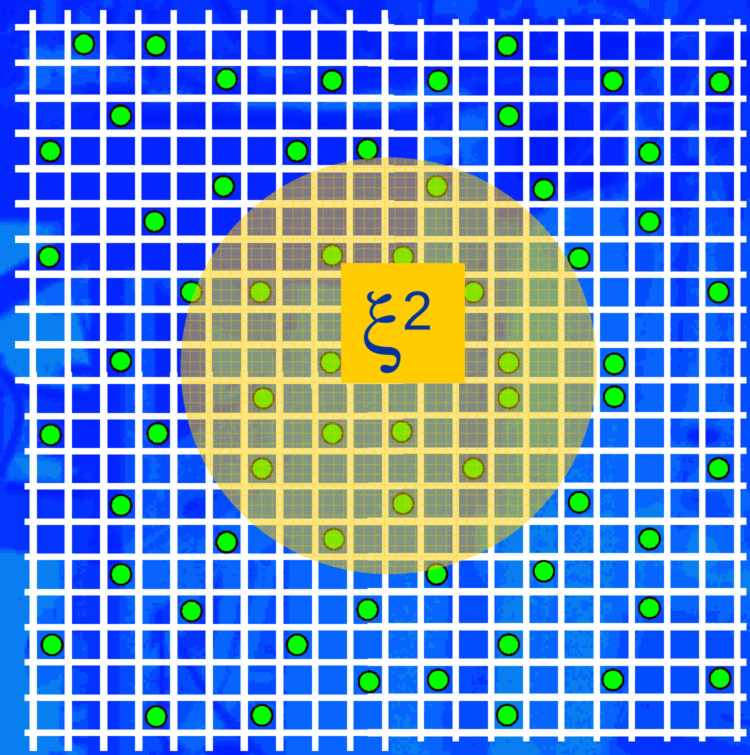
« OXYDES A PROPRIETES REMARQUABLES »
Aussois, 9-15 juin 2002

Supraconductivité à haute Tc

$Bi_2Sr_2CaCu_2O_{8+\delta}$ $\delta_{opt} \approx 0{,}16$

$\xi \sim$ 2-3 nm

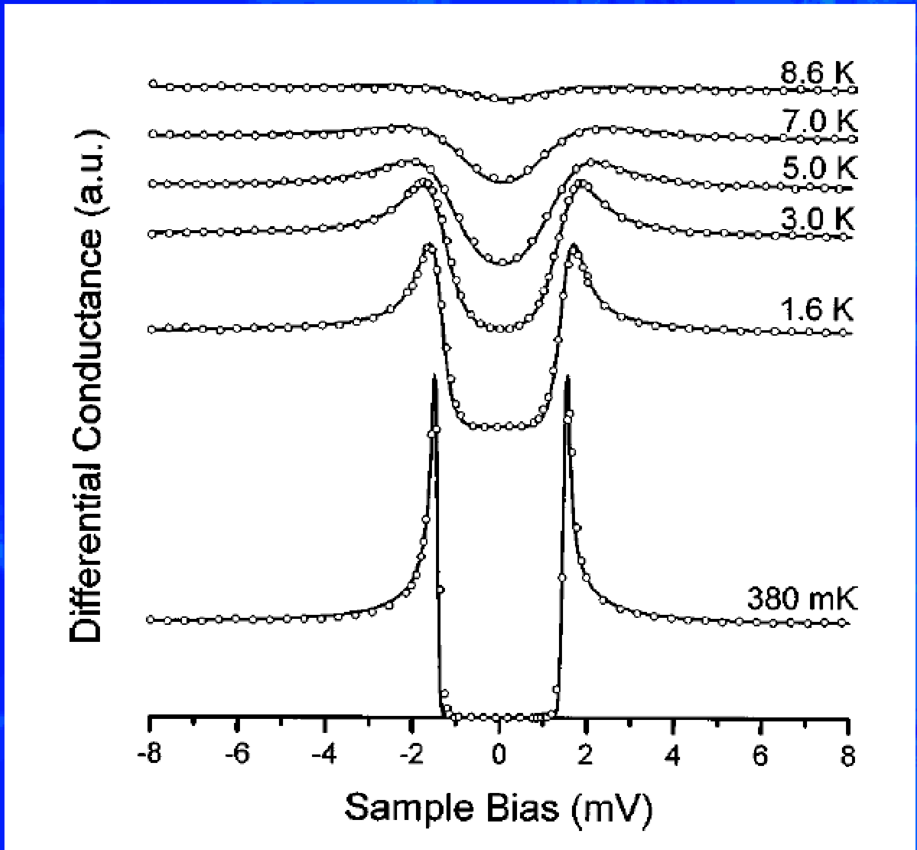


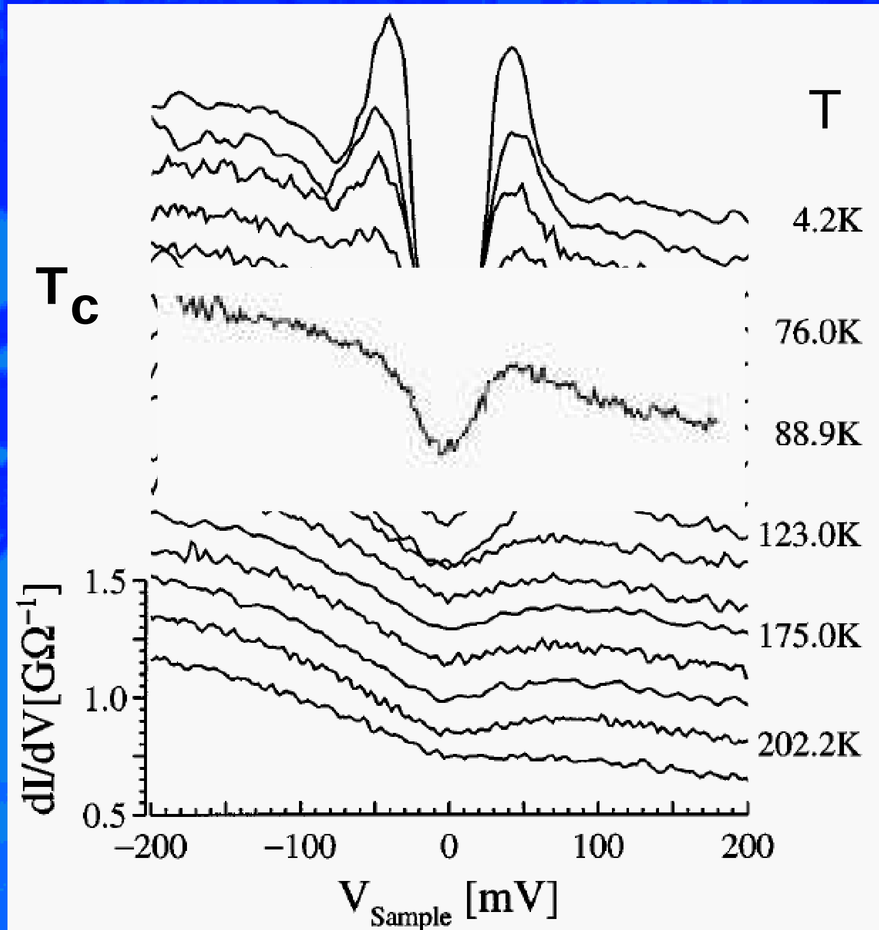


« OXYDES A PROPRIETES REMARQUABLES »
Aussois, 9-15 juin 2002

Supraconductivité à haute Tc : Gap

- *Jonction Nb-Au.*
- *$Bi_2Sr_2CaCu_2O_{8+\delta}$-Pt/Ir.*





Pan, Davis,
Univ. de Berkley.(1998)

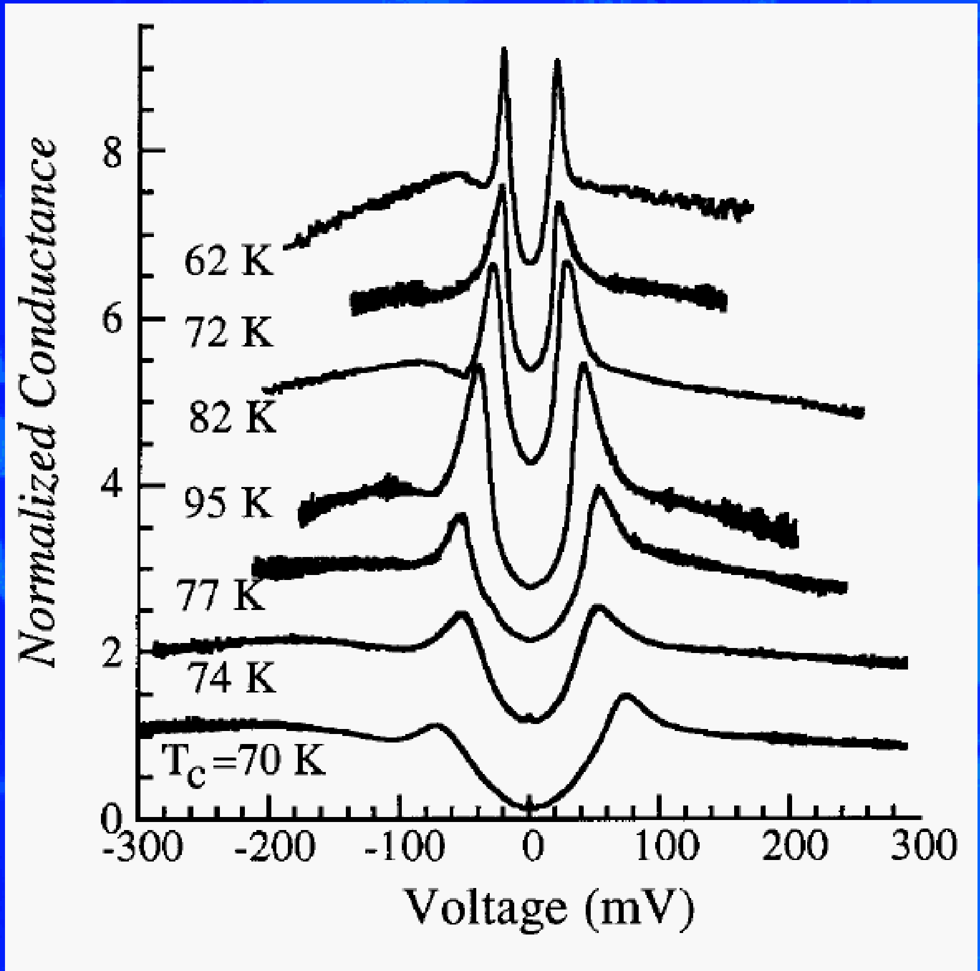
$$\frac{2\,\Delta(0)}{kT_c} \approx 3{,}5$$

$$\frac{2\,\Delta(0)}{kT_c} \approx 38$$

Ch. Renner, Ø. Fisher,
Univ. de Genève. PRL (1998)

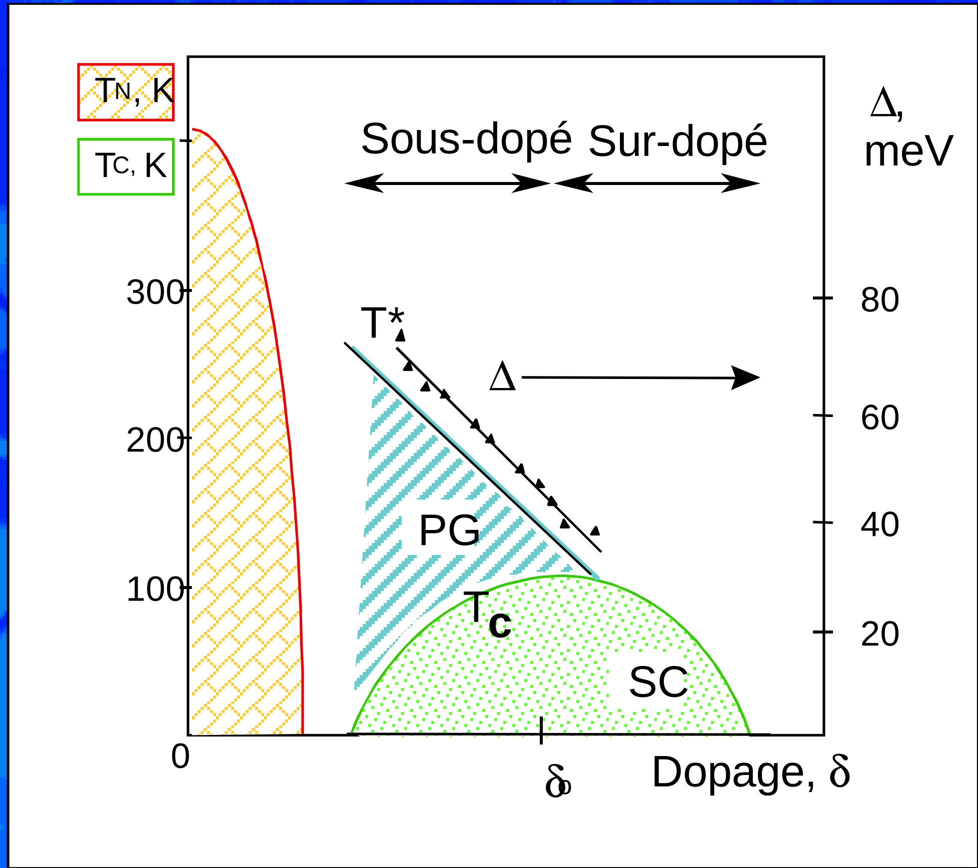
Supraconductivité à haute Tc : Dopage

- $Bi_2Sr_2CaCu_2O_{8+\delta}$-Pt/Ir.



Miyakawa, Zasadzinski, PRL (1999)

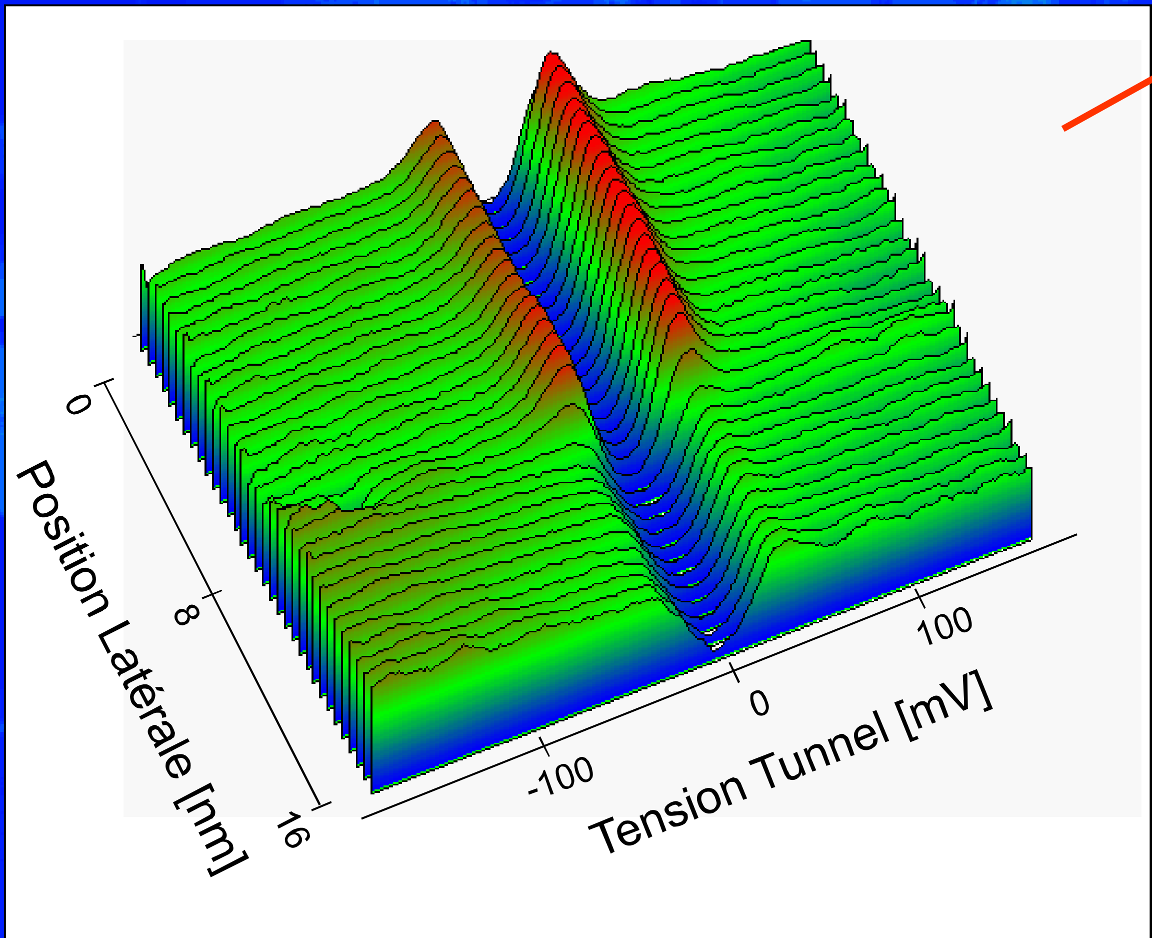
- Gap vs dopage.



$$\frac{2\Delta(0)}{kT_c} \approx 5\text{-}60$$!

Pseudo-gap existe à basse température !

- Spectroscopie locale à l'échelle du nanomètre (couches minces de $Bi_2Sr_2CaCu_2O_{8+\delta}$)

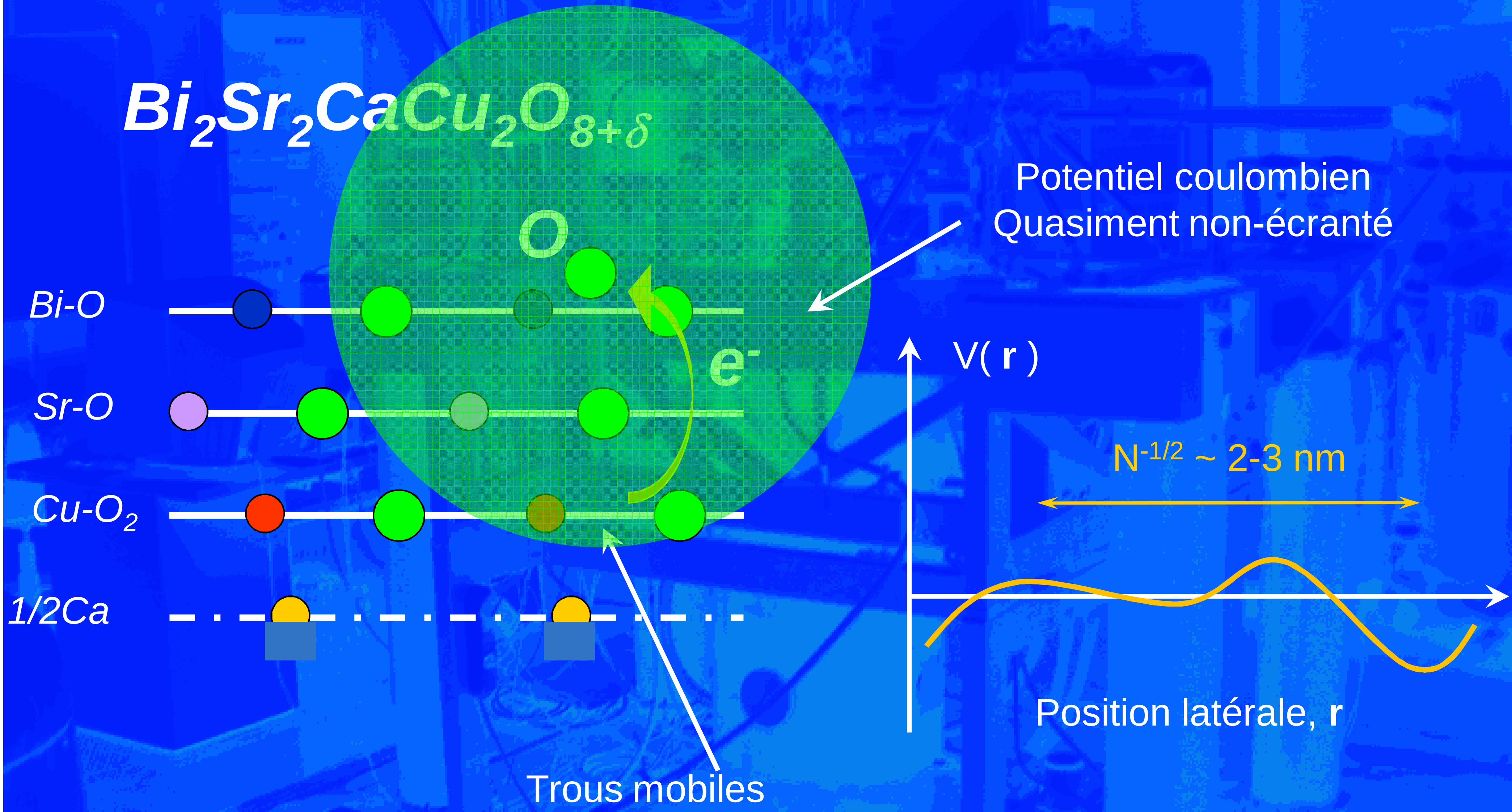


T. Cren et al. Phys. Rev. Lett., 84, 1 (2000)

PG induit par le désordre ?

Collaboration INSP-ESPCI et INSP-CRISMAT

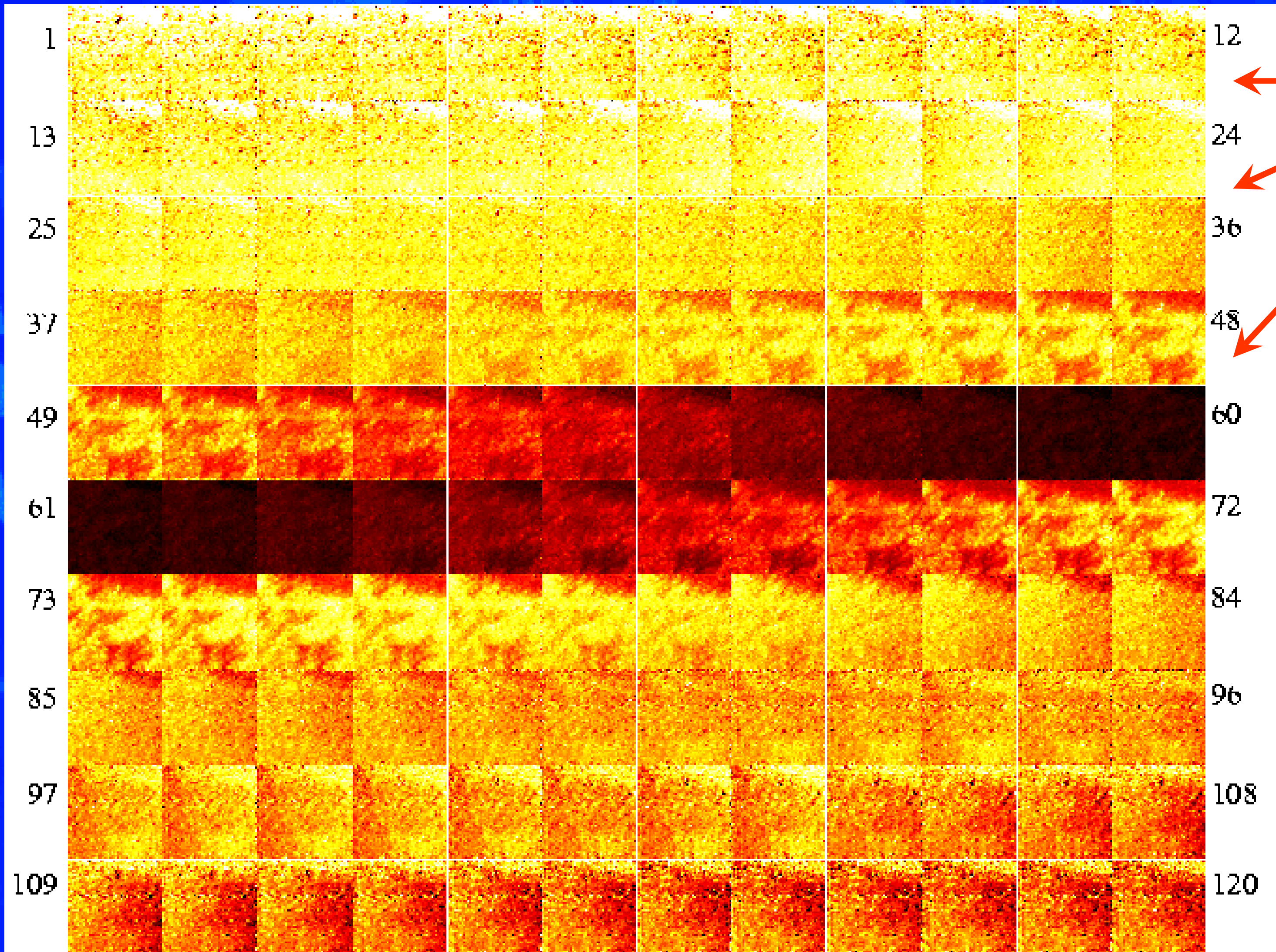
Cuprates et désordre



« OXYDES A PROPRIETES REMARQUABLES »
Aussois, 9-15 juin 2002

Influence du désordre substitutionnel

- STS sur des monocristaux de $Bi_{1-X}Pb_XSr_2CaCu_2O_{8+\delta}$



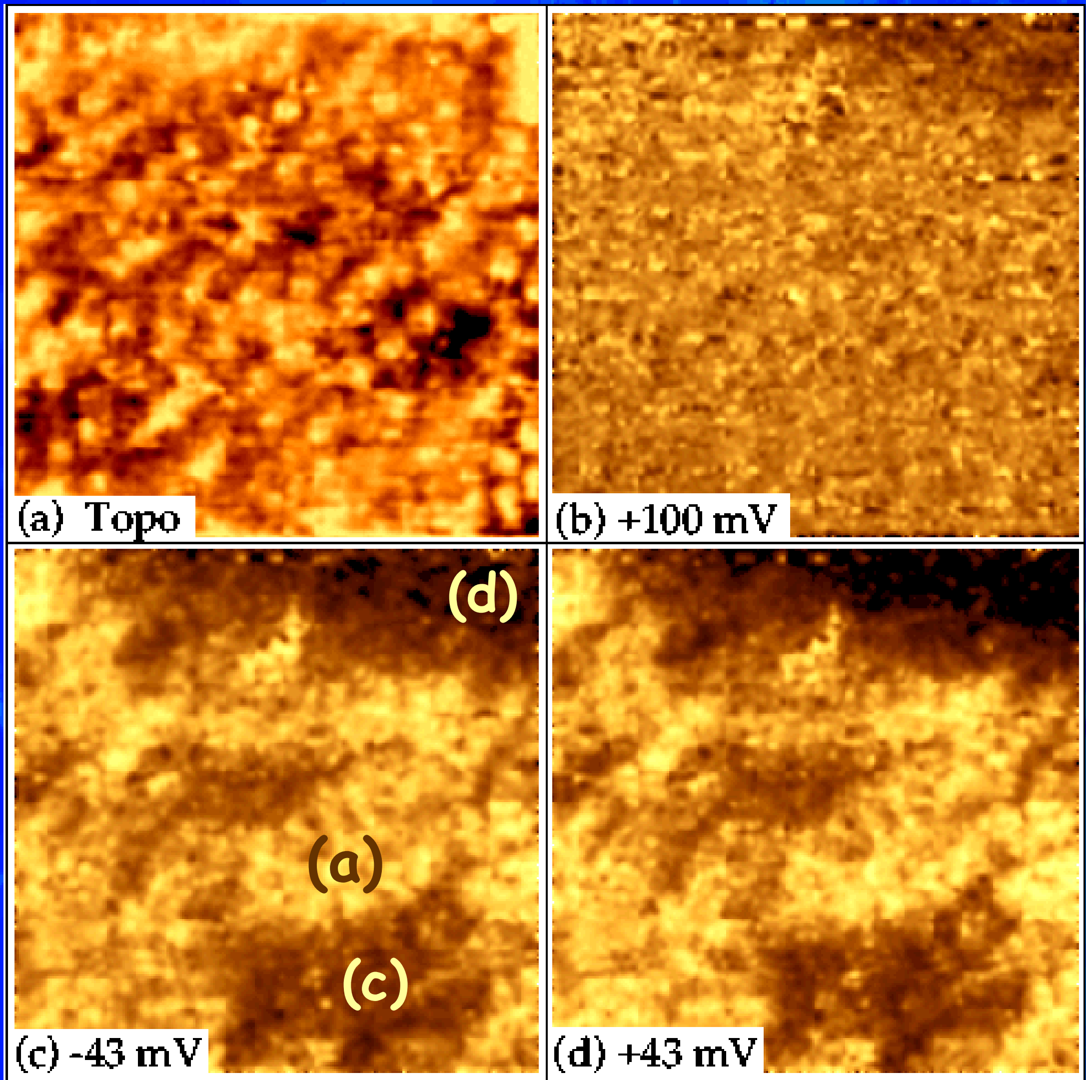
Images LDOS 150nm x 150nm

Energie varie de –240meV à + 240meV

T.Cren, D. Roditchev et al. EPL (2001)

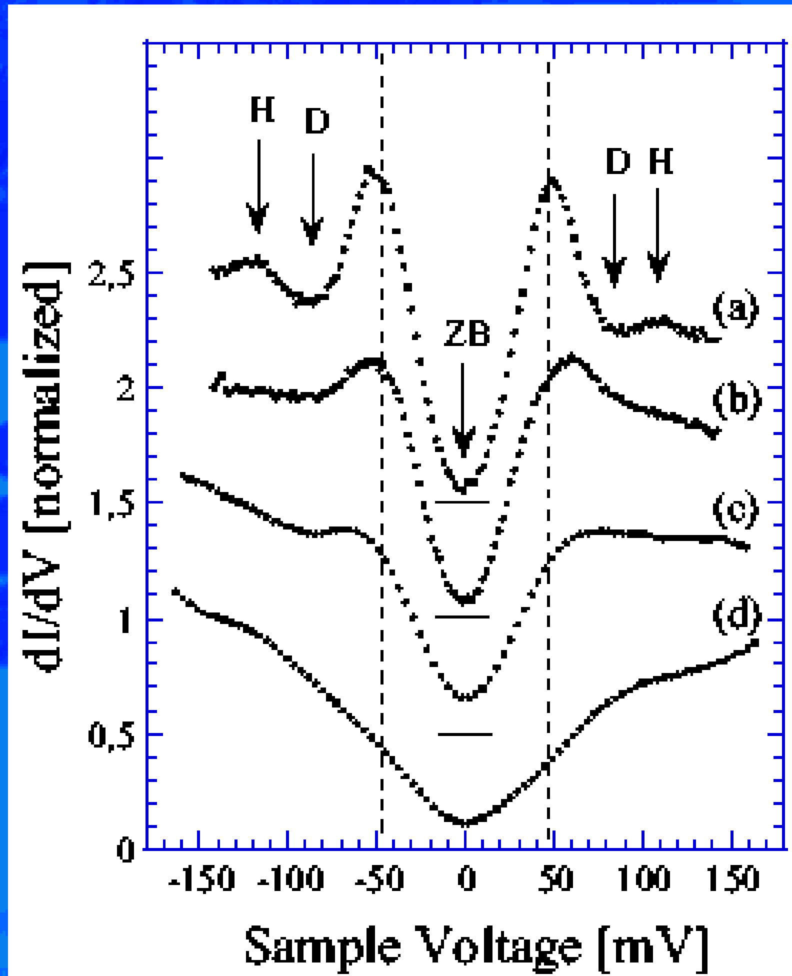
Influence du désordre substitutionnel

- Images LDOS 150nm x 150nm

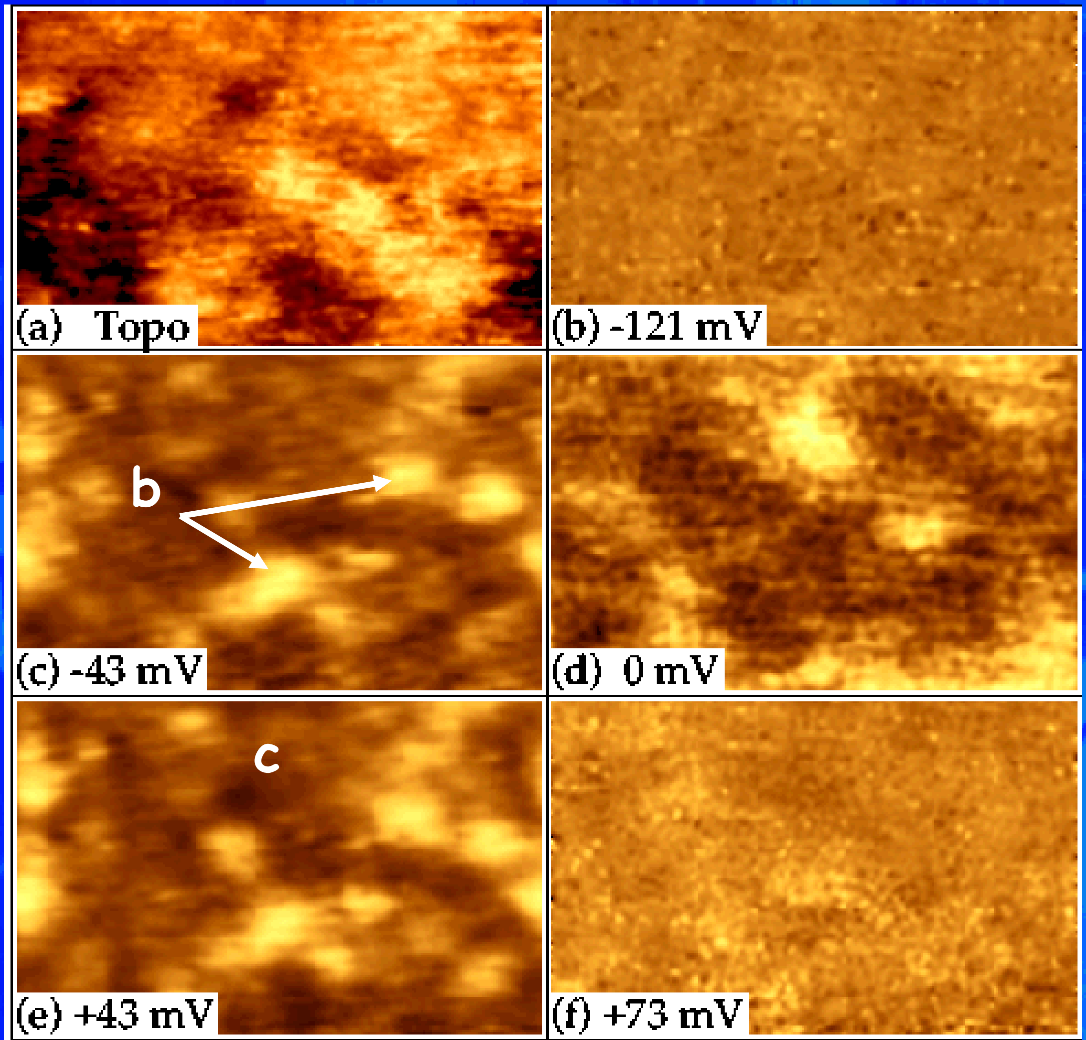


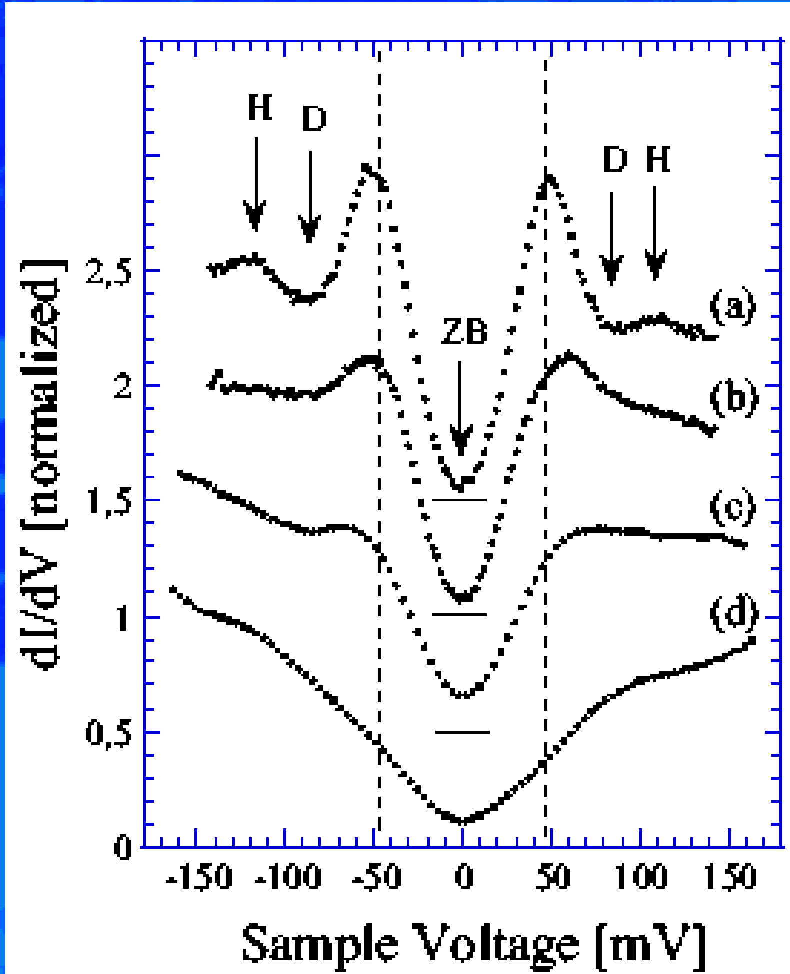
T.Cren, D. Roditchev, W. Sacks, J. Klein, et al. Europhys. Lett. (2001)

- Spectres tunnels



Influence du désordre sur la supraconductivité des cuprates

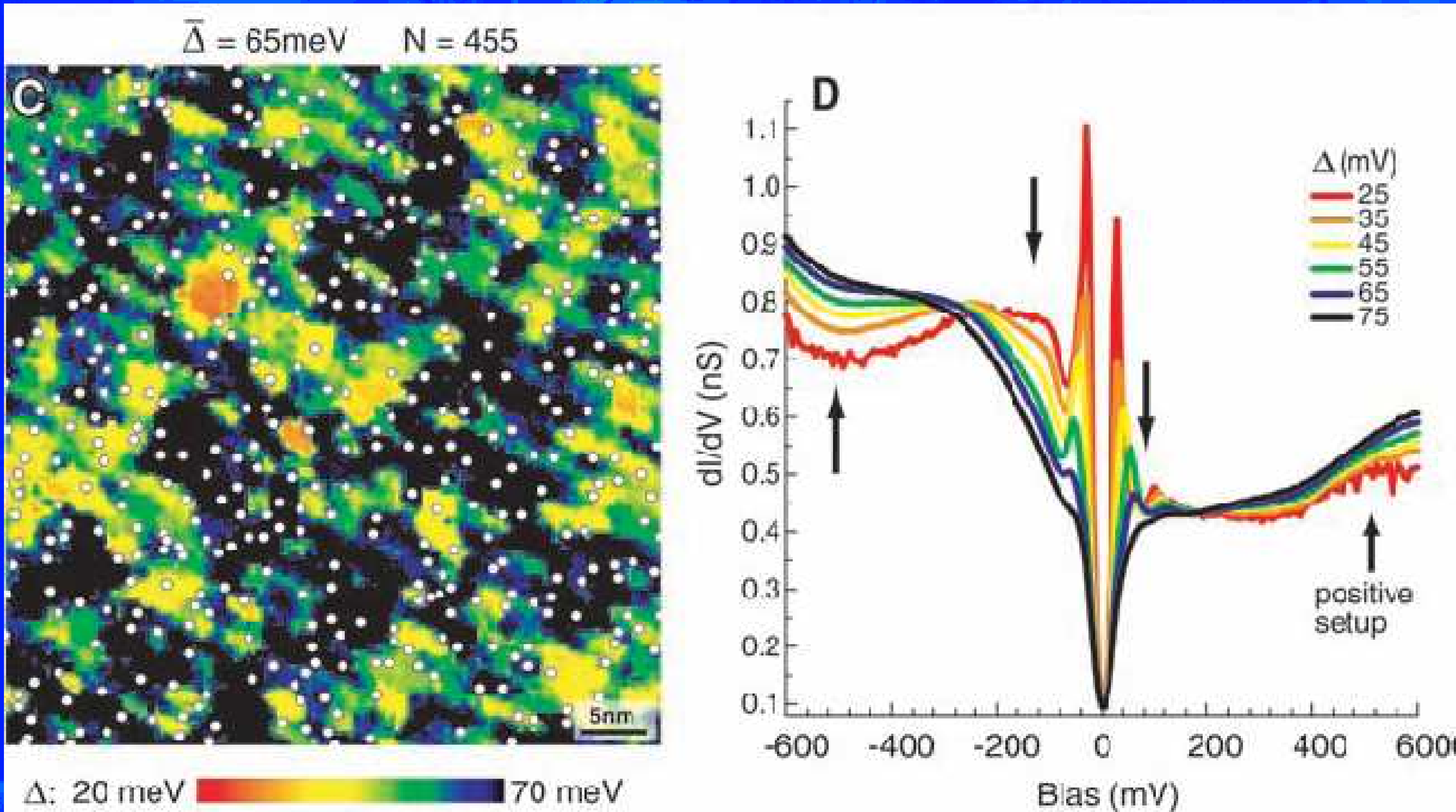




Collaboration ESPCI

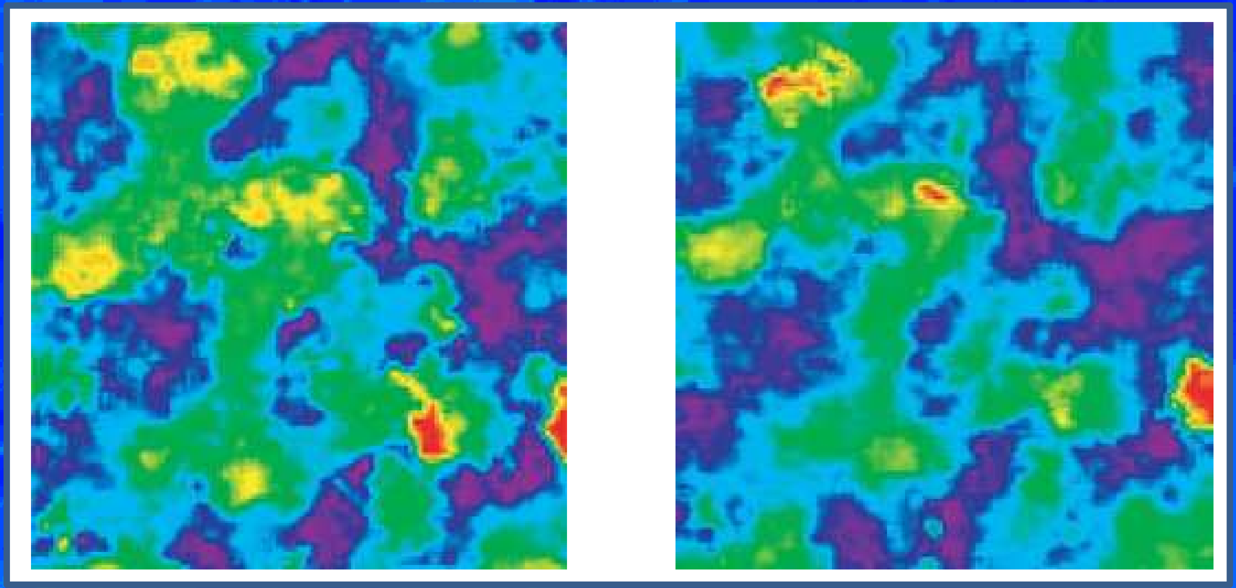
T. Cren, D. Roditchev, et al.
Europhys. Lett., 54(1), 84-90 (2001)

Influence du désordre:
10 ans d'études en STM/STS



Cross-correlations among the simultaneously measured Z(r,V), Δ(r) and O(r) images showing a clear correlation between the gap, the oxygen and the structural disorders.

Influence du désordre: 10 ans d'études en STM/STS



Gap-map @5K, T<Tc **Gap-map @17K, *T>Tc***

Hudson et al., Nat. Phys. 3, 805 (2007)

Conclusion

<u>STM/STS: Advantages</u>:

Extraordinary spatial and eneregy resolution

Quasi-direct access to the DOS and its spatial extend

Possibility to explore (H,T) phase diagram

<u>STM/STS: Weak Points</u>:

Extreme sensitivity to the surface (states, quality etc.)

Poorely controlled ***k***-selectivity

High electric field may be perturbative

Experimentally heavy approach